Stability of Calcium Sulfate Base Course in a Wet Environment

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16. Abstract

Blended Calcium Sulfate (BCS) is fluorogypsum (FG), an industrial by-product, blended with lime or limestone. Approximately 90,000 metric tons (100,000 tons) of FG are generated annually in the United States, posing a serious problem for environmental disposal. The Louisiana Department of Transportation and Development (LA DOTD) has been using BCS in pavement construction over the last 15 years. While this material has performed satisfactorily after construction, its moisture sensitivity has concerned LA DOTD engineers because it has presented construction difficulty in wet environments. Therefore, there is a need to better understand the strength deterioration of BCS in a wet environment, and find ways to eliminate or reduce such deterioration by stabilizing BCS with various suitable cementitious agents.

This study was divided into two major parts: laboratory and field tests. Laboratory tests were conducted to identify factors that significantly affect the strength development of raw BCS and to seek a suitable stabilization scheme for ameliorating water susceptibility of raw BCS. The effectiveness of each stabilization scheme was evaluated from the perspective of water resistance, strength, and volumetric expansion incurred by stabilization. Laboratory tests also investigated the resilient modulus and permanent deformation characteristics of stabilized BCS. Samples tested in the laboratory included ones both molded in the laboratory and cored at the test section of the Pavement Research Facility (PRF) test site at the Louisiana Transportation Research Center (LTRC).

The field test program included two parts: (1) building a full-scale test section at the PRF site according to proposed construction specifications; and (2) evaluating the performance of stabilized BCS base courses through in-situ tests, such as DCP, FWD, and DYNAFLECT to characterize their strength and structural properties.

Ground granulated blast furnace slag (GGBFS) with a grade of 120 was used to stabilize BCS to improve its water resistance in this study. Portland cement, lime, and fly ash were also used as additives to GGBFS with different proportions to improve the properties of GGBFS-stabilized BCS.

The results from this study indicate that moisture content controlled the strength of raw BCS, although other factors such as dry unit weight also influenced the result. Curing conditions affect the strength of raw BCS through the change of moisture content in the material. The loss and regaining of strength is generally a reversible process and the presence of free water among gypsum crystal particles is the reason for this phenomenon. BCS stabilized by 10 percent 120-grade GGBFS by volume can serve as a good pavement base. It achieved a fairly higher stiffness and a structural layer coefficient of 0.30 can be used for pavement design purpose. The tentative construction specifications (Appendix A) used in the study proved to be adequate for the field construction. Therefore, it can be used with minor modification for future projects. Researchers recommend that the LA DOTD consider building several field test sections in different traffic and environmental conditions using the GGBFS-stabilized BCS as pavement base course.

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ABSTRACT

Blended Calcium Sulfate (BCS) is fluorogypsum (FG), an industrial by-product, blended with lime or limestone. Approximately 90,000 metric tons (100,000 tons) of FG are generated annually in the United States, posing a serious problem for environmental disposal. The Louisiana Department of Transportation and Development (LA DOTD) has been using BCS in pavement construction over the last 15 years. While this material has performed satisfactorily after construction, its moisture sensitivity has concerned LA DOTD engineers because it has presented construction difficulty in wet environments. Therefore, there is a need to better understand the strength deterioration of BCS due to the moisture intrusion, and find ways to eliminate or reduce such deterioration by stabilizing BCS with various suitable cementitious agents.

This study was divided into two major parts: laboratory and field tests. Laboratory tests were conducted to identify factors that significantly affect the strength development of raw BCS and to seek a suitable stabilization scheme for ameliorating water susceptibility of raw BCS. The effectiveness of each stabilization scheme was evaluated from the perspective of water resistance, strength, and volumetric expansion incurred by stabilization. Laboratory tests also investigated the resilient modulus and permanent deformation characteristics of stabilized BCS. Samples tested in the laboratory included ones both molded in the laboratory and cored at the test section of the Pavement Research Facility (PRF) test site at the Louisiana Transportation Research Center (LTRC).

The field test program included two parts: (1) building a full-scale test section at the PRF site according to proposed construction specifications; and (2) evaluating the performance of

stabilized BCS base courses through in-situ tests, such as DCP, FWD, and DYNAFLECT to characterize their strength and structural properties.

Ground granulated blast furnace slag (GGBFS) with a grade of 120 was used to stabilize BCS to improve its water resistance in this study.   Portland cement, lime, and fly ash were also used as additives to GGBFS with different proportions to improve the properties of GGBFS-stabilized BCS.

The results from this study indicate that moisture content controlled the strength of raw BCS, although other factors such as dry unit weight also influenced the result.   Curing conditions affect the strength of raw BCS through the change of moisture content in the material.   The loss and regaining of strength is generally a reversible process and the presence of free water among gypsum crystal particles is the reason for this phenomenon.   BCS stabilized by 10 percent 120-grade GGBFS by volume can serve as a good pavement base.   It achieved a fairly higher stiffness and a structural layer coefficient of 0.30 can be used for pavement design purpose. The tentative construction specifications (Appendix A) used in the study proved to be adequate for the field construction.   Therefore, it can be used with minor modification for future projects. Researchers recommend that the LA DOTD consider building several field test sections in different traffic and environmental conditions using the GGBFS-stabilized BCS as pavement base course.

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IMPLEMENTATION STATEMENT

This study identified free moisture content as the predominant factor responsible for the high water susceptibility of non-stabilized BCS.   Therefore, the researchers recommend not using raw BCS directly as a pavement base material in wet environments. BCS stabilized by 10 percent 120-grade GGBFS by volume can serve as a good pavement base.   The researchers recommend that the LA DOTD consider using the construction specifications similar to that (Appendix A) used in the study to build several field test sections of the GGBFS-stabilized BCS as pavement base course in different traffic and environmental conditions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Fluorogypsum (FG) is an industrial by-product of hydrofluoric acid from fluorspar (a mineral composed of calcium fluoride) and sulfuric acid. It is discharged in a slurry state and then gradually solidifies into a dry state in holding ponds. Approximately 90,000 metric tons (100,000 tons) of FG are generated annually in the United States, mostly in Delaware, New Jersey, Louisiana, and Texas, posing a serious problem for environmental disposal *[1]*. Currently, there is no successful major recycling program for this waste material.

In Louisiana, FG is required to be treated with lime or limestone before recycle to raise its pH value for environmental safety and, thus, is commonly referred to as Blended Calcium Sulfate (BCS). BCS can be a good base course material if used properly and using BCS in highway construction will significantly reduce the cost and be greatly beneficial to the recycling program and environment protection in Louisiana.

BCS can achieve high strength and stiffness in a dry condition, but has trouble in either achieving or sustaining the adequate strength to maintain traffic loads in a wet environment. The Louisiana Department of Transportation and Development (LA DOTD) has been using BCS in pavement construction over the last 15 years *[2, 3]*. While this material has performed satisfactorily on projects after construction, its moisture sensitivity has concerned LA DOTD engineers because it causes construction difficulty in wet environments, as shown in figure 1. Therefore, there is a need to better understand the strength deterioration of BCS in wet environments and find ways to eliminate or reduce such deterioration by stabilizing BCS with various suitable cementitious agents.

Figure 1
Pavement with a non-stabilized BCS base course

Past Experience with FG and BCS

Limited experimental applications of stabilized FG in highway pavements suggested that it could be used as a base material *[4, 5]*. The earliest documented use of FG in a pavement base was the construction of the TRANSPO'72 International Transportation Exposition held in 1972 at Dulles Airport near Washington, D.C. In this project, a small amount of FG (2.5 percent) was mixed with 2.5 percent lime, 62 percent fly ash, 18 percent bottom ash, and 13 percent crushed limestone together. In a separate case, four test sections of a plant-haul road with a lime-fly ash stabilized FG base were constructed in August 1981 at the Allied Chemical Company plant in Nitro, West Virginia *[5]*. The amount of FG was increased to 75 percent in one tested section, while it generally ranged from 30 percent to 65 percent in the other three sections. FG's water susceptibility was not mentioned in these projects.

In Louisiana, a number of projects previously constructed with BCS base courses were evaluated with the Falling Weight Deflectometer (FWD) and the Dynamic Cone Penetrometer (DCP). Table 1 presents some results of this evaluation conducted by Louisiana Transportation Research Center (LTRC). A soil cement base course on LA 16 was also evaluated for comparison. The DCP results herein were interpreted by penetration per blow (mm/blow), which is inversely proportional to strength. The average values reported in table 1 showed that BCS base course could achieve adequate strength (2,470

MPa (358 ksi) or 3.3 mm/blow) when compared to soil-cement base course (3,260 MPa (473 ksi) or 1.4 mm/blow). However, a single site reading taken on Jefferson Highway over a broken joint resulted in a DCP reading of 50 mm/blow, which indicated a negligible strength. This measurement could be an indication of water infiltration.

Table 1
Summary of BCS base course test sections

Blended Calcium Sulfate				
Sites		FWD		DCP
LA 16 - Watson to Wiess		2360 MPa (342 ksi)		3.4 mm/blow
LA 3002		628 MPa (91 ksi)		5.3 mm/blow
LA 1034		5147 MPa (746 ksi)		2.0 mm/blow
LA 16 Denham Springs		1677 MPa (243 ksi)		2.2 mm/blow
LA 73 - Jefferson Highway		NA		3.5 mm/blow
Average		2470 MPa (358 ksi)		3.3 mm/blow
Soil Cement				
LA 16		3260 MPa (473 ksi)		1.4 mm/blow

In 2002, LTRC monitored two other construction projects with BCS base course: (1) Relocated LA 1 in Lafourche Parish and (2) Evangeline Thruway in Lafayette Parish. The base course in Relocated LA 1 was constructed on a free draining sand embankment, while the base course in Evangeline Thruway was constructed in a depressed location that did not have good drainage. Thus, the pavement structures at the Evangeline Thruway were subjected to severe rainwater ponding after each storm. Figure 2 presents the DCP test results at six locations conducted periodically after initial compaction of the base course. After initially gaining strength with time and curing (about 30 days), half of the test locations began to lose strength rapidly, as illustrated by the increase in the DCP penetration

per blow in figure 2. Most likely, this strength loss was caused by water infiltration that occurred during this period.
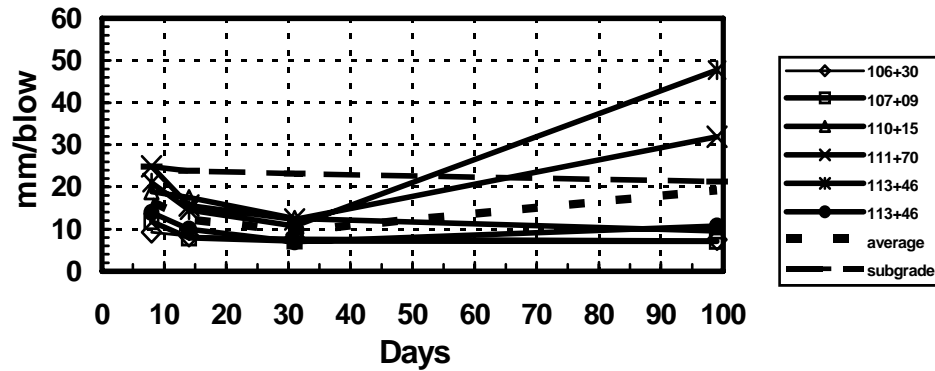
Figure 2
DCP results (Evangeline Thruway, Louisiana)

The remainder of the project was randomly tested with the DCP and FWD. The results averaged 7.8 mm/blow for the DCP test with a corresponding modulus of 59 ksi (407 MPa) from the FWD tests.   These values are substantially less than those listed in table 1. The average values for the Relocated LA 1 project were 3.1 mm/blow and 86 ksi (593 MPa) from the DCP and FWD, respectively. While these values are higher than those in the Lafayette project, they are also lower than the previous readings taken on the same project. In short, BCS base course tends to decrease in shear strength and stiffness in pavements with poor drainage. This field observation corroborated the deterioration of BCS base course in a wet environment. Previous studies also indicated that gypsum materials, including the BCS, had poor water resistance, and were expected to lose up to 50 percent of their dry strength when as little as 2 percent of the water was absorbed*[6, 7, 8]*.

Some stabilization agents such as Portland cement were used to improve the water resistance of gypsum materials *[9]*. Although most Portland-cement-stabilized materials are strong and durable in moist conditions, the cement is not a good agent for stabilizing gypsum materials. One local parish reported that BCS expanded and caused heaving when

exposed to cement (personal communication, 2002). Ettringite is usually formed quickly when gypsum materials are stabilized with Portland cement. This formation of ettringite is responsible for detrimental expansion and leads to significant strength deterioration. Therefore, it is usually unadvisable to ameliorate the water resistance of BCS with Portland cement.

Kovler reported the successful stabilization of gypsum with a blend of Portland cement and silica fume *[10]*. In his study, 75 percent gypsum was blended with 25 percent Portland cement-silica fume mixture (by weight), with the optimal Portland cement/silica fume ratio of 1:1. This mixture's wet/dry strength ratio was 0.6 after 200 days of water immersion. A gypsum-Portland cement-silica fume blend with the optimal ratio specified by Kolver may be feasible for certain civil engineering applications. However, such a stabilization scheme will not be cost effective for BCS used as a highway base due to the relatively high costs of Portland cement and silica fume. Apart from the cost concern, mixing silica fume in field construction is still a technical challenge. As a result, stabilizing BCS with the Portland cement-silica fume blend is not feasible or advisable.

Phase transition *[11]* between various gypsum bearing minerals, as shown in figure 3, is another factor considered in the design and conduct of laboratory tests on FG or BCS. In an ordinary oven at $120^{o}C$, not only will free moisture in BCS evaporate, but some structural moisture can also be lost, which will not occur in the field. Thus, a special drying condition is specified to ensure that only free moisture content of BCS will be measured. According to Taha's study, no appreciable amount of structural moisture is lost up to $70^{o}C$ for phosphogypsum, as shown in figure 4 *[12]*. Phosphogypsum is also an industrial waste product, which has chemical composition similar to that of FG, but comes from a different source.
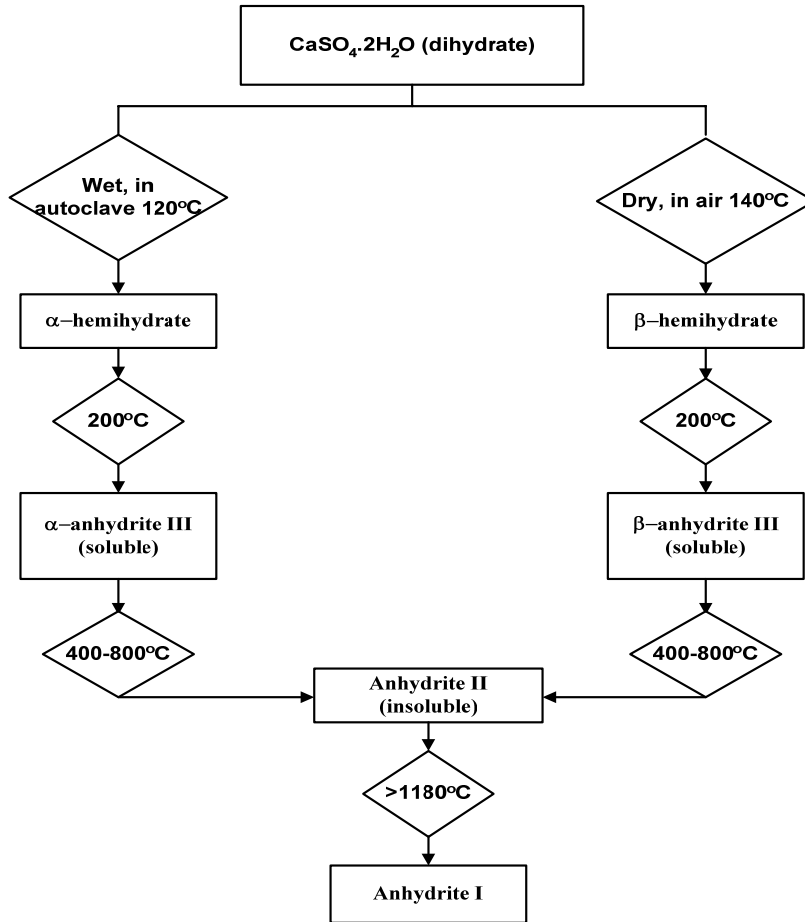
Figure 3
Phase transition of gypsum bearing minerals *[11]*
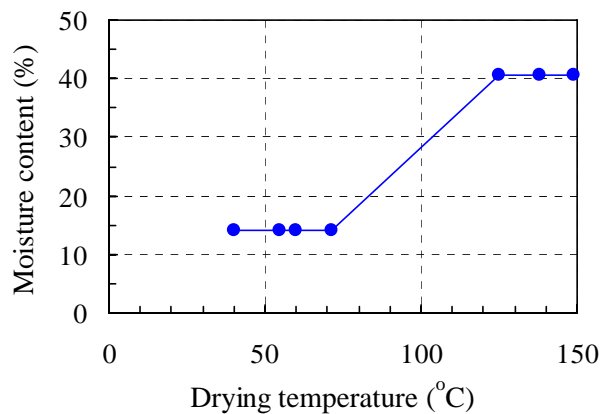
Figure 4
Moisture content of phosphogypsum versus drying temperature (after *[12]*)

OBJECTIVE

The objectives of this study were to: (1) identify the important factors affecting the strength development of non-stabilized BCS, (2) find cost-effective and technically feasible stabilization agents to ameliorate water vulnerability of BCS, and (3) evaluate field performance of stabilized BCS with construction specification developed and tested by building a full-scale test section.

SCOPE

Basic properties of BCS with and without stabilization were characterized in this study through both laboratory and in-situ tests. The laboratory tests included the unconfined compressive strength (UCS), repeated loading triaxial, volumetric expansion, and drying-wetting durability tests. The field testing study included the construction of a full-scale test section at LTRC's pavement research facility (PRF), dynamic cone penetrometer (DCP), falling weight deflectometer (FWD), and dynamic deflection determination system (DYNAFLECT) tests. Cementitious agents used to stabilize BCS in this study were grade 120 ground granulated blast-furnace slag (GGBFS), Type I Portland cement, lime, and Type C fly ash.

METHODOLOGY

This study was divided into two major parts: laboratory and field tests. In this report, the original BCS is referred to as raw BCS, while its aggregate portion passing and remaining on a No. 4 sieve are referred to as minus-4 and plus-4 BCS, respectively. Since the properties of fine particles of BCS control its moisture susceptibility, a forensic study in the laboratory on BCS was conducted on the portion of BCS passing a No. 4 sieve with an equivalent diameter less than 4.75mm. BCS with the entire gradation was used in the laboratory only to investigate the engineering properties of field-mixed stabilized BCS such as unconfined compressive strength, resilient modulus, and permanent deformation, and in the field test to validate the stabilization results obtained in the laboratory.

Laboratory tests were conducted to identify factors that significantly affect the strength development of raw BCS and to seek a suitable stabilization scheme for ameliorating water vulnerability of raw BCS. The effectiveness of each stabilization scheme was evaluated from the perspective of water resistance, strength, and volumetric expansion incurred by stabilization. Laboratory tests also investigated resilient modulus and permanent deformation characteristic of stabilized BCS. Samples tested in the laboratory included both molded in the laboratory and cored at the test section of the PRF test site.

The field test program included two parts: 1) building a full-scale test section at the LTRC's PRF site according to proposed construction specifications, and 2) evaluating the performance of stabilized BCS base courses through in-situ tests, such as DCP, FWD, and DYNAFLECT to characterize their strength and structural properties. Pavement structural layer coefficient of stabilized BCS was estimated accordingly for pavement design purposes.

Laboratory Testing Program

Laboratory tests were conducted to determine general properties of BCS, investigate the mechanism responsible for the strength deterioration of raw BCS in a wet environment, and characterize mechanical behavior of stabilized BCS samples.

Materials

Bear Industries Inc., Port Allen, LA, supplied the BCS used in this study. This material had a pH value of 6.5. Its chemical components are listed in table 2.

Table 2
Chemical compositions of BCS under investigation

Compositions	Percentage by weight
SiO_2	0.5
Al_2O_3	0.1
Fe_2O_3	0.2
CaO	29.0
SO_4	54.0
CO_3	3.0
Moisture	5-30

Buzzi Unicem USA located in New Orleans, LA, provided the ground granulated blast-furnace slag (GGBFS), which complied with ASTM C989 with a grade 120. GGBFS is manufactured from blast furnace slag, a by-product of iron products, which is a glassy, homogeneous, non-crystalline material with cementitious properties. Other cementitious agents used for comparison in this study included Type I Portland cement, Class C fly ash, and lime. Their chemical compositions are listed in table 3. The fly ash used in the field test section was also supplied by Bear Industries, Inc.

Table 3
Chemical constituents of used stabilizers *[2]*

Composition (%)	Portland Cement[a]	Fly Ash[b]	GGBFS[c]
SiO_2	22.4	47.5	34.5
Al_2O_3	4.1	4.1	9.5
Fe_2O_3	3.9	5.2	1.3
CaO	65.1	20.1	39.6
MgO	1.2	2.5	10.9
K_2O	0.2	0.7	1.3
Na_2O	0.1	0.3	0.5

[a] type I Portland cement; [b] Class C fly ash; and [c] the grade 120 ground granulated blast furnace slag.

Conventional Test Methods

Basic Tests. The basic properties of BCS mixtures included their gradation, moisture content, dry density, and compaction curves.   Therefore, laboratory tests included conventional tests such as the gradation analysis (ASTM D 422) *[13]*, specific gravities (ASTM D854) *[14]*, compaction curves with various compaction energy (ASTMs D 698 and D1557) *[15, 16]*, etc.

Apparatus for Moisture Content. An apparatus called CoreDry, as shown in figure 5, was used in addition to a conventional oven to determine the moisture content of BCS. This device dries samples by vacuuming them at a controlled temperature and was calibrated in the laboratory with a low-temperature (40°C) conventional oven.

Figure 5
Picture of CoreDry device

Unconfined Compressive Strength (UCS) Test. UCS tests were conducted in the laboratory with the United "Smart-1" Test System (SFM 30) in accordance with ASTM D1633 *[17]*. Testing data were automatically recorded by data acquisition software.

4" specimen. Specimens with a diameter of 4 inches (102.0 mm) and a height of 4.584 inches (116.0 mm) were prepared for BCS passing No. 4 sieve. Sample preparation followed ASTM D698 and D 1557, except that 3 layers and 41 blows per layer were used for the modified compaction. The 3-layer compaction was used to reduce the number of interfaces within a specimen, and the 41 blows count was determined to assure the same compaction level as specified in ASTM D 1557.

6" specimen. Specimens with a diameter of 6 inches (152.4 mm) and a height of 4.584 inches (116.0 mm) were prepared in the laboratory for field mixed BCS with its entire gradation. Sample preparation followed ASTM D 1557.   Specimens cored from the field test section also had a diameter of 6 inches (152.4 mm), but a height of 11.6 to 11.9 inches (294.6 - 302.3 mm).

Forensic Study of UCS for Non-stabilized BCS

The factors that most likely affect the development of UCS for non-stabilized BCS included dry density, curing conditions, and moisture content. Four sets of non-stabilized BCS samples were molded to identify the influence of these factors on BCS's strength.

Dry Density. The first set of specimens with three designed moisture contents and three designed dry unit weights were molded to investigate the influence of dry unit weight on strength. A "compression" procedure was used to achieve the required dry unit weight and moisture content. The compression procedure is summarized as follows:

- Measure the required amount of BCS and water according to predetermined moisture content and dry unit weight;
- Mix them thoroughly and allow them to set for thirty minutes; and
- Pour the water-BCS mixture into a cylindrical mold and statically compress it to

a specific height for a required dry density with a hydraulic compression device. All samples were then cured in air for 28 days to reach an almost dry condition before testing. Thus, it is reasonable to exclude moisture's influence on UCS.

Curing Time. The second set of samples was molded by the modified Proctor procedure discussed previously at the same initial moisture content, and cured in a 100 percent relative humidity room for different time durations before testing.   These samples were then tested to evaluate the effect of curing times on their strength.

Moisture Content. The last two sets of samples were used to assess the influence of free moisture on BCS's strength. They all were molded by the modified Proctor procedure at the same initial conditions, but cured at different environment.   One set of samples was cured so that different moisture contents in the specimens were achieved at the sample break for strength (wet→ dry).   The other set of specimens was initially cured and totally dried in air and then exposed to water for various time periods (dry→wet).   The equilibrium of moisture in the re-dampened samples was achieved by wrapping the samples in plastic bags and putting them in a 100 percent relative humidity room for 48 hours.   The time needed to achieve the moisture equilibrium was determined on the basis of relatively uniform moisture contents at different portions of samples. After their moisture reached equilibrium within the samples at different moisture contents, these re-dampened samples were then loaded to evaluate the impact of moisture content on the strength of BCS.

Special Test Methods

Extra tests were conducted on stabilized BCS to investigate its special properties and described as follows.

Volumetric Expansion. The strength gain of stabilized BCS is primarily attributed to hydration or pozzolanic reactions between BCS and added cementitious agents. This strength improvement was often accompanied by undesirable volumetric changes. Excessive volumetric deformation during the strength development, which usually takes time, can cause

severe premature damage in the field after construction. Therefore, the volumetric deformation of each stabilized BCS samples must be evaluated and understood over their curing duration.

The test samples had the same size as the regular 4 inch specimen for the UCS test. They were molded at the optimum moisture content with a modified proctor and cured in a 100 percent relative humidity room between measurements.

The ASTM C490 specification is usually adopted to monitor the volumetric expansion of concrete materials *[18]*. However, this standard procedure is not directly applicable to stabilized BCS samples. Stabilized BCS entails necessary mechanical compaction, but the comparator used in ASTM C490 does not accommodate the dimensions of stabilized BCS samples. Instead, an alternative procedure was adopted. A caliper with a resolution of 0.001 inch (0.01 mm) was used, which was comparable to the resolution of the comparator in ASTM C490. Initial diameters and heights of these samples were recorded and their values were subsequently measured at various curing ages. The volumetric expansion was characterized by volumetric strain, shown in equation 1.

$$\varepsilon_{vol} = \frac{V - V_0}{V_0} \times 100\% \qquad (1)$$

Where, V_0 and V are the initial and current volumes of a sample, respectively.

Durability Tests under Wetting and Drying Conditions. Durability is the property of a pavement material that reflects its long-term performance under freeze-thaw and wetting-drying cycles during its service life. Since freeze-thaw rarely occurs in pavement layers in Louisiana, only wetting-drying cycles are of concern in this study. The durability of GGBFS-stabilized BCS samples was evaluated by undergoing 12 wetting-drying cycles in accordance with ASTM D559 *[19]*. This test assesses mass losses, water content changes, and volume changes (swelling and shrinkage) caused by repeated wetting and drying cycles. The sample preparation procedure for durability tests was the same as that for the volumetric

expansion test. After 12 wetting and drying cycles, the mass losses and volumetric change were determined for each tested sample.

Repeated Loading Triaxial Test. Repeated loading triaxial test (RLT) is customarily the procedure to determine resilient modulus of pavement materials in the laboratory. AASHTO T-294 test protocol was used in this study *[20]*.

Specimen Preparation. A 6 inch by 13 inch split mold and a vibratory compaction device were used for preparing samples, as shown in figure 6. Two membranes were used to prevent any damage caused by coarse particles, with the aid of vacuum to achieve a good contact with the mold. Samples were prepared by six two-inch lifts to achieve the uniform compaction throughout the specimen. A predetermined amount of the materials was poured into the mold at each lift. Each layer was then compacted until the required density was obtained as indicated by the distance from the top of the mold to the surface of the compacted layer. The surface of each lift was then lightly scratched to achieve good bonding with the next lift. The compacted samples were 6 inch by 12 inch (diameter by height) cylinders.

Figure 6
Compaction of stabilized BCS with entire gradation

Testing. RLT tests were conducted on these samples after 7 and 28 days of curing at the confining and deviator stress levels recommended in the AASHTO T-294 procedure. The load sequence used in this study is listed in table 4, with a loading pulse cycle shown in figure 7. Each loading cycle consists of a 0.1-second loading period and a 0.9-second rest period.

Table 4
AASHTO T294-94 loading sequences [20]

Sequence	σ_3 (psi)[a]	σ_d (psi)[b]	Number of cycles
0 (conditioning)	15	15	1000
1	3	3	100
2	3	6	100
3	3	9	100
4	5	5	100
5	5	10	100
6	5	15	100
7	10	10	100
8	10	20	100
9	10	30	100
10	15	10	100
11	15	15	100
12	15	30	100
13	20	15	100
14	20	15	100
15	20	15	100

[a] Confining pressure; and [b] deviatoric stress.
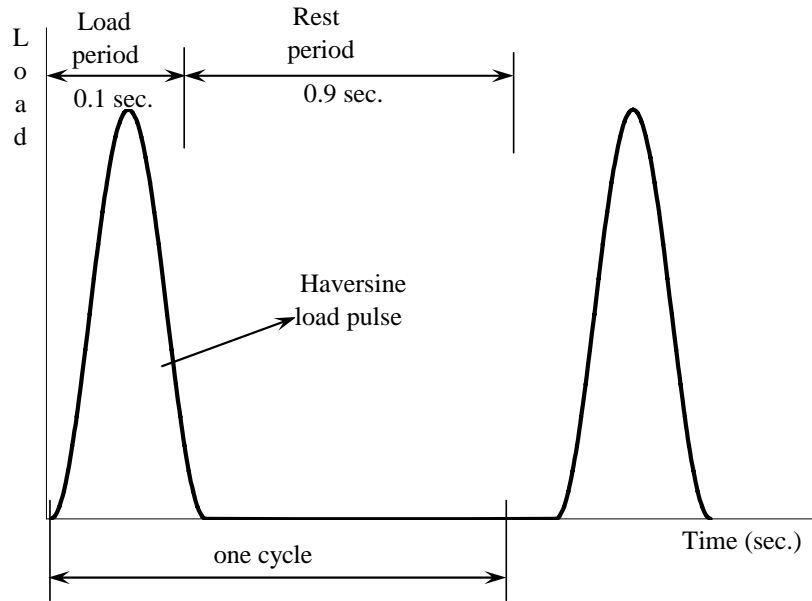
Figure 7
Load pulse used in RLT tests

Permanent Deformation. Pavement materials respond to traffic loading both elastically and plastically. Its elastic response, i.e. resilient characteristic, has been extensively studied and widely used in pavement designs and assessment. However, its plastic response, i.e. permanent deformation, has received little attention even though it is responsible for pavement rutting to some extent, which is one of the most common pavement distresses. The permanent deformation of the stabilized BCS was evaluated through testing on the samples cured after 28 days. The tested samples were the same used in the resilient modulus tests. Ten thousand cycles of repeated loading were applied to the samples under a confining pressure of 15.0 psi (103.4 kPa) and a deviator stress of 15.0 psi (103.4 kPa) to obtain the permanent deformation data.

BCS Stabilization

Ten percent of GGBFS by weight was used in the laboratory to stabilize BCS to improve its water resistance in this study. This selection was based on the literature search, previous experience, and a trial and error test in the laboratory. The water resistance of BCS

is characterized by the ratio of UCS determined in submersion and dry states (UCS_w/UCS_d,

where UCS_w and UCS_d represent the UCS of a submerged (or wet) sample and of an un-submerged (or dry) sample, respectively). A higher water resistance obtained after stabilization indicates the effectiveness of that stabilization scheme which includes both the type and quantity of the agent. Portland cement, lime, and fly ash were also used as additives to GGBFS with different proportion to improve the properties of GGBFS stabilized BCS.

Other percentages of GGBFS ($<$ 10 percent by weight) were also tested in addition to the 10 percent by weight of GGBFS, but the results were not conclusive due to the poor quality of GGBFS used (different batch of supply).

The influence of curing conditions, which included both curing humidity and age, on stabilization effect was first investigated through three different curing relative humidity: 50 percent, 65 percent (regular indoor rooms), and 100 percent at room temperature (73^oF) with various curing durations. It was concluded that only 100 percent relative humidity gave the best strength development of stabilized BCS. Therefore, this was the only curing relative humidity used in the rest of the study.

GGBFS Stabilization. The specimens of GGBFS stabilized BCS tested in the laboratory included laboratory mixed and molded of minus-4 BCS, field mixed and laboratory molded of regular BCS with its entire gradation, and field cored of regular stabilized BCS. The laboratory mixed BCS stabilized with 10 percent GGBFS by weight was mixed with tap water and molded using the modified Proctor at the targeted initial moisture content, which was 3 percent over the optimum moisture content in accordance with the modified Proctor procedure. The mixture was allowed to slake for 5 hours. The samples used for UCS test were cured in a 100 percent relative humidity room and tested after 7, 14, or 28 days of curing; the ones for volumetric expansion test were cured in a 100 percent relative humidity room between measurements; and the ones for durability test were cured in

a 100 percent relative humidity room for 28 days (wrapped in plastic bags). See test methods for more details.

Field mixed BCS with its entire gradation was stabilized with 10 percent GGBFS by volume, which was from the 10 percent GGBFS by weight for the minus-4 BCS mixed in the laboratory. The plus-4 BCS, which was about 50 percent of the entire BCS gradation, did not need to be stabilized. So theoretically, only 5 percent by weight or 8 percent by volume of GGBFS was needed to stabilize BCS in the field. Ten percent GGBFS by volume was finally adopted in the field with the consideration of uncertainty in the field mixing condition. Equation 2 defines the conversion between percent by weight, $\%_{weight}$, and percent by volume, $\%_{volume}$.

$$\%_{volume} = \frac{\gamma_{d,BCS}}{\gamma_{d,GGBFS}} \cdot \%_{weight} \qquad (2)$$

Where $\gamma_{d,BCS}$ is the dry unit weight of BCS determined by the standard proctor and 110 lb/ft^3 was used; $\gamma_{d,GGBFS}$ is the dry unit weight of GGBFS and 70 lb/ft^3 was used in this study.

The samples used for the UCS test were 6 inches in diameter and 4.584 inches in height in accordance with ASTM D1557 method C. After compaction, the samples were wrapped in plastic bags and cured in a 100 percent relative humidity room for various timeframes (7, 14, or 28 days). For each sample set, two samples were tested immediately after curing while the other two were tested after being submerged in water for 4 hours. UCSs tested without soaking and after 4-hour submersion in water are referred to as un-soaked and soaked UCS, respectively.

The samples used for the RLT in the laboratory were 6 inches in diameter and 12 inches in height. The RLT tests were conducted on these samples after 7 and 28 days of curing at the confining and deviator stress levels recommended in the AASHTO T-294 procedure. The permanent deformation of the field mixed stabilized BCS was conducted on the same samples after 28 days of curing and the resilient modulus analysis. The cored GGBFS-stabilized samples from the field test section at the LTRC's PRF site were also

tested for their resilient modulus and permanent deformation.   The results were compared with these of the samples molded in the laboratory.

GGBFS Stabilization with Additives. GGBFS-stabilized BCS with other cementitious additives, such as type I Portland cement, lime, and class C fly ash, were also tested in the laboratory for their strength, volumetric change, and permanent deformation. These tests were planned and conducted to improve the engineering properties of GGBFS-stabilized BCS.   The test procedures are the same as those for the GGBFS stabilized BCS.   Table 5 shows the factorial schemes used in this study for their strength and volumetric changes.

Table 5
Samples prepared to determine an optimum stabilization scheme

Cementitious Mixtures	Proportions	Additive Concentration (%)	Age (days)
GGBFS+Lime	5:1	4,6,9	7
GGBFS+Cement	3:1	4,6,9	7
GGBFS+Lime+Fly ash	3:1:2	4,6,9	7
GGBFS+Cement+Fly ash	3:2:1	4,6,9	7

Field Testing Program

The field test program of this research was in conjunction with another LTRC research project (03-2GT): Accelerated Loading Evaluation of a Sub-base Layer on Pavement Performance.   Six field test sections were built at the LTRC's PRF site with two of them designated, 4-1A and 4-2A, for the stabilized BCS.   One was of GGBFS stabilized BCS with 10 percent by volume; the other was fly ash stabilized BCS with 15 percent by volume. Due to the relatively low cost of fly ash, this material was used to mix with BCS in one of the field test sections to see whether it would enhance BCS's field performance.

Figure 8 presents the layout and cross-section profiles of six test sections for the accelerated loading test. Each testing section was 108 ft. long and 13 ft. wide. Lane 4-1A

consists of a 12-inch lime treated sub-base with 10 percent lime by volume, an 8.5 inch BCS base stabilized with the grade 120 GGBFS, and a 2 inch Superpave wearing course; Lane 4-2A consists of a 12-inch lime treated sub-base with 10 percent lime by volume, an 8.5-inch BCS base treated with class C fly ash, and a 2-inch Superpave wearing course. At the end of Lane 4-2A, a 30-foot long raw BCS subsection was built for comparison. The information of other test sections is shown in table 6 for reference.
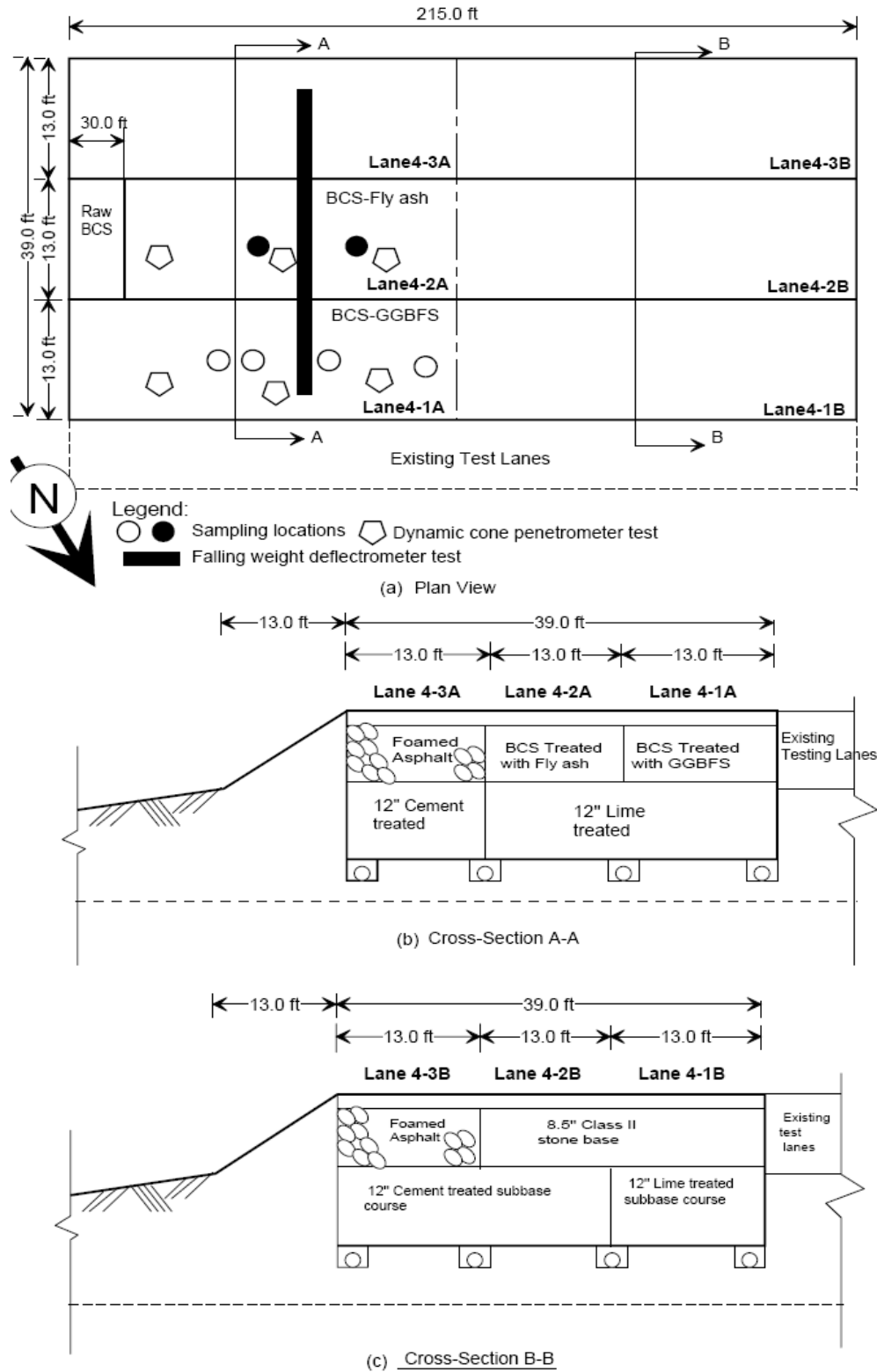
Figure 8
Schematic layout of test section: (a) plan view; (b) cross-section A-A; and (c) cross-section B-B

Table 6
Summary of field test sections at PRF site

Test Section	AC wearing course, inch	Base course	Sub base course
4-1A	2	8.5" GGBFS stabilized BCS 10% by volume	12" lime treated, 10% by volume
4-2A	2	8.5"fly ash stabilized BCS 15% by volume	12" lime treated, 10% by volume
4-3A	2	8.5" foamed asphalt [50/50 blend of RAP (Reclaimed Asphalt Pavement) and soil cement]	12 " cement treated, 8% by volume
4-1B	2	8.5" crushed stone	12" lime treated, 10% by volume
4-2B	2	8.5" crushed stone	12 " cement treated, 8% by volume
4-3B	2	8.5" foamed asphalt (100 percent RAP) treated base	12 " cement treated, 8% by volume

Construction

Appendix A at the end of this report details the construction specifications used in this study for the raw and GGBFS stabilized BCS base courses.   The construction of fly ash stabilized BCS base course followed the same specifications as the GGBFS stabilized BCS base course used except the 15 percent of fly ash by volume.

BCS was delivered to the PRF site and placed evenly over the finished subgrade at the required thickness of 8.5 inches using a Case 850C dozer for Lanes 4-1A and 4-2A. The BCS layer was slightly compacted prior to stabilization execution. Next, 10 percent GGBFS by volume and 15 percent class C fly ash by volume were placed over the BCS layers on Lanes 4-1A and 4-2A, respectively, and blended using a Caterpillar SS250 stabilizer. Two passes of the stabilizer were conducted with extra water added in the second pass to the fly ash treated BCS base but not the GGBFS stabilized BCS base. The decision was based on the field observation since the water needed was controlled by the field experience. The fly ash treated BCS base was built first and water was added to it. The mixture on each lane

was subsequently compacted using a multi wheel rubber tire roller. It was noticed that the water added to the base courses went into the lime treated subgrade layer without much moisture change in base materials themselves. The compaction on the base courses stopped when the bases started to weave under the multi wheel rubber tire roller or no further improvement on dry unit weight. The entire construction of stabilized BCS was conducted under a wet environment and this can be seen from the field DCP data shown late. To prevent water from evaporating, the finished bases were sealed with a layer of asphalt tack coat as a required field curing condition. The whole stabilization procedure is illustrated with photos in figure 9.

Figure 9
Photos of the stabilization process of BCS

Field Moisture Control

The original plan was to use the CoreDry device to control the field construction moisture because of its short duration for drying a sample. However, due to the lack of experience of using the device in field, it was not recognized during the construction that the device was automatically shut down by itself during the field shipping and handling to protect itself. Since the construction could not wait, the field moisture content was controlled by personal

experience. The field moisture content of the various materials was obtained later by the 40°C oven or the CoreDry machine in the laboratory after construction.

Sampling during Construction and Field Coring at the PRF Test Sections

BCS materials stabilized with GGBFS or fly ash were collected at the PRF testing sections immediately after they were thoroughly mixed, as shown in figure 10. The collected mixtures were then brought back to the laboratory at LTRC and molded for the samples of UCS, resilient modulus, and permanent deformation tests. In addition, some samples were cored directly from the PRF testing sections after a 35-day curing in the field and tested for their UCS, resilient modulus, and permanent deformation characteristics in the laboratory. These samples were cored in Lanes 4-1A and 4-2A, as illustrated in figure 11.

Figure 10
Sampling stabilized BCS for laboratory tests
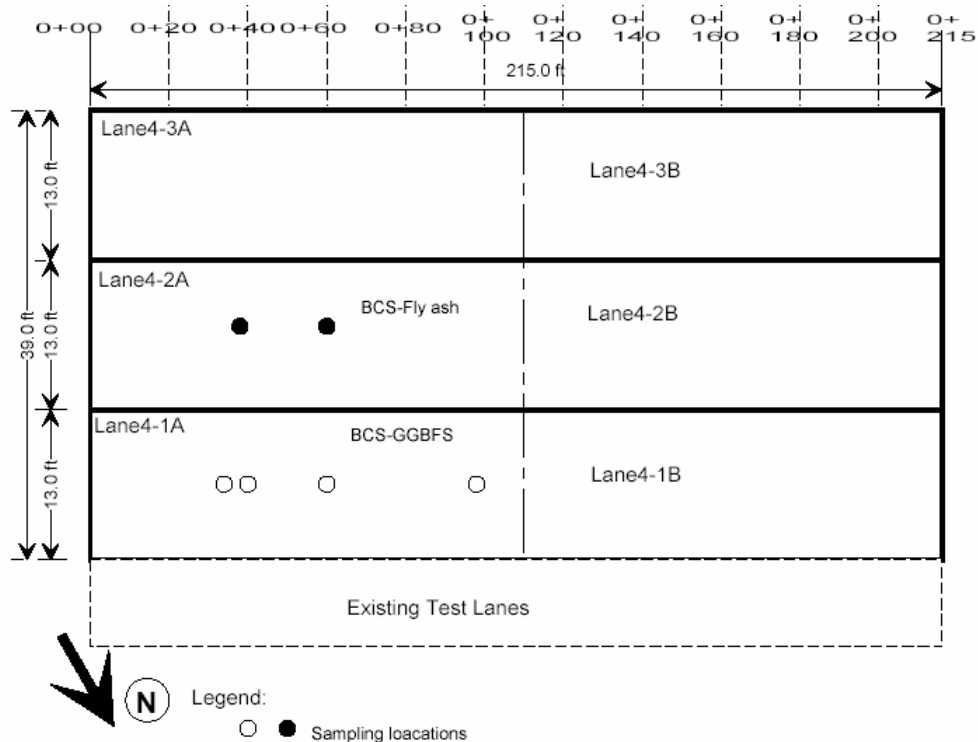
Figure 11
Locations of cored samples at PRF test sections

In-Situ Tests

Dynamic cone penetrometer (DCP), falling weight deflectometer (FWD), and Dynamic Deflection Determination System (DYNAFLECT) were used to assess in-situ mechanical behavior of stabilized BCS at the PRF testing sections.

Dynamic Cone Penetrometer (DCP). DCP is a simple and effective tool for evaluating in-situ strength of pavement layers and subgrade *[21]*. Figure 12 shows the DCP device used in this investigation. It consists of an upper fixed 22.7 in. (575 mm) travel rod with a 17.6 lb (8 kg) falling weight hammer, a lower rod containing an anvil, and a replaceable 60° cone of 3/4 in. (20 mm) diameter. It provides continuous measurements of in-situ strength of subgrade soils without sampling. The test involves lifting and dropping the 17.6 lb (8 kg) hammer to strike the anvil, and to penetrate the 3/4 in. (20mm) diameter

cylindrical cone from the surface down to the required depth.
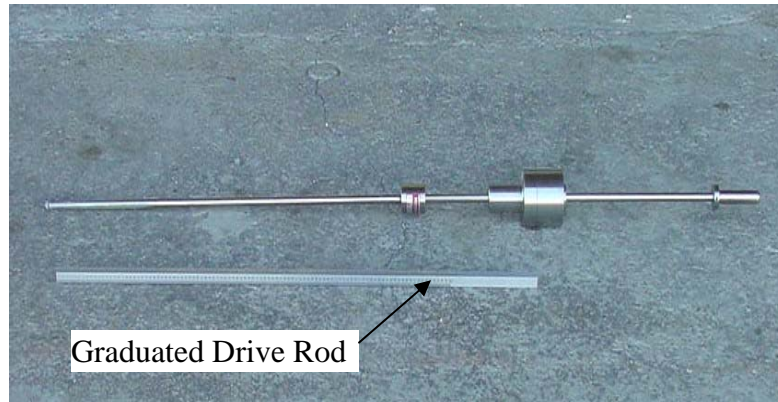
Figure 12
Dynamic cone penetrometer used in this study

Falling Weight Deflectometer Tests (FWD). FWD is a trailer-mounted device that delivers an impulse load to the surface under investigation. The equipment automatically lifts a weight to a given height. The weight is dropped onto a 12 in. (300 mm) circular load plate with a thin rubber pad mounted underneath. A load cell measures the force or load applied to the pavement under the plate. Seven sensors measure the deflections caused by the impulse load. The first sensor is always mounted in the center of the load plate while sensors two through seven are spaced at various distances (0, 12, 18, 24, 36, 48, 60 in. or 0, 305, 457, 610, 914, 1219, and 1524 mm) from the load center. Changing the mass of the falling weight and/or the drop height varies the impulse load. The DYNATEST 8002 FWD was used in this study, as shown in figure 13. FWD tests were conducted on the sub-base, base, and surface layers of the testing sections at various curing ages.

Figure 13
Dynatest 8002 falling weight deflectometer

Dynamic Deflection Determination System (DYNAFLECT). DYNAFLECT is a trailer mounted device which induces a dynamic load on the pavement and measures the resulting deflections by using geophone sensors, usually five, spaced under the trailer at approximately 1 ft. (300 mm) intervals from the application of the load.   DYNAFLECT with Model Number 1000-8A was used in this study. In this test, a pavement is subjected to 1,000 lbf (4.45 kN) of dynamic load at a frequency of 8 Hz, which is produced by two counter rotating unbalanced flywheels. The cyclic force is transmitted vertically to the pavement through two steel wheels spaced 20 in. (508 mm) from center-to-center. The dead load plus dynamic force during each rotation of the flywheels varies from 1,100 to 2,100 lbf (4.9 to 9.3 kN) and generates a typical DYNAFLECT deflection basin as shown in figure 14. DYNAFLECT tests were only conducted on the finished surface layer (Superpave wearing course) of the testing sections at various curing ages.
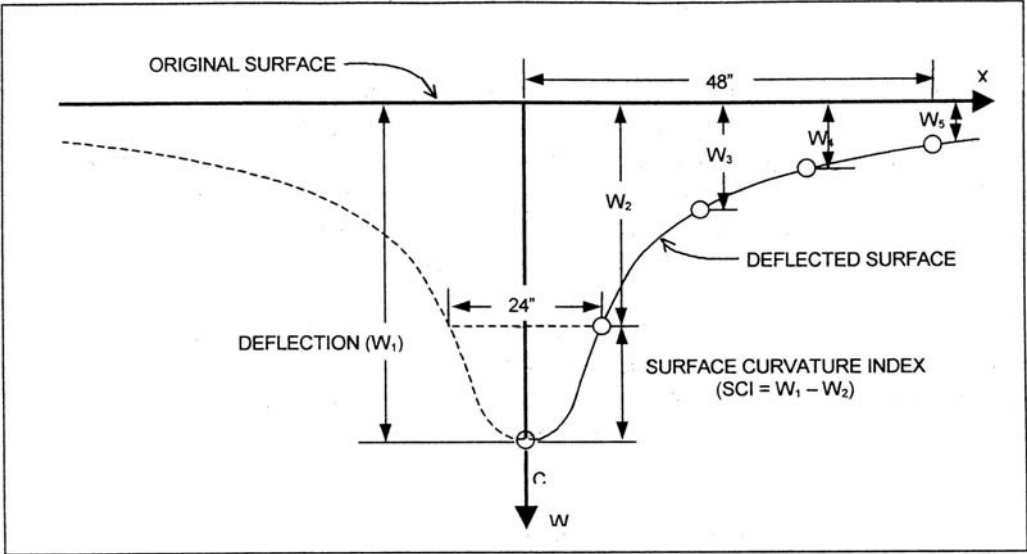
Figure 14
Typical DYNAFLECT deflection basin

DISCUSSION OF RESULTS

Results of this study included the laboratory evaluation, field validation, and analysis on the results of laboratory and field testing data.

Laboratory Evaluation

Laboratory results are presented in three parts: the general performances of non-stabilized BCS, stabilized BCS mixed and molded in the laboratory, stabilized BCS mixed in the field and molded in the laboratory or cored from the field.

Non-Stabilized BCS

General Properties of Non-Stabilized BCS. Figure 15 shows the particle size distribution curve of BCS with uniformity coefficient $C_u = 150$ and the coefficient of curvature $C_z = 24$. Accordingly, BCS is classified as equivalent to GM (Unified Classification System) or A-1-a (AASHTO Soil Classification System). Figure 15 also shows, for comparison, the particle size distribution curve of crushed limestone specified by LA DOTD specifications as Class II Base Course material. Therefore, the BCS tested in this study can also be classified as Class II Base Course material from the gradation point of view.
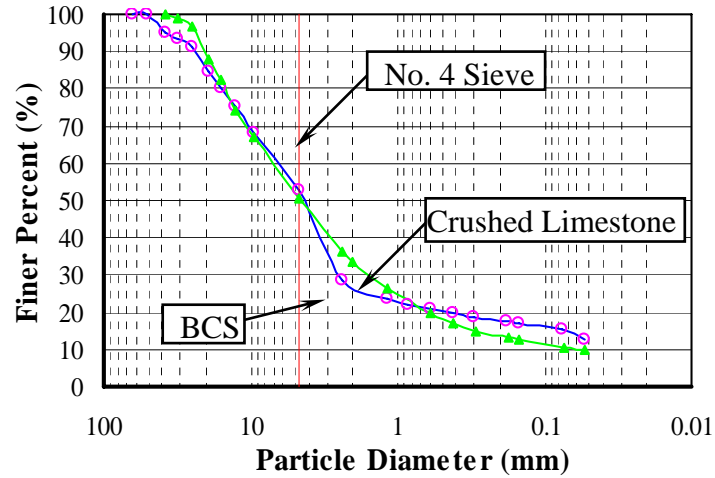
Figure 15
Particle size distribution of blended calcium sulfate (BCS)

The gradation of BCS is not stable during construction due to the breaking down of big chunks of gypsum.   Figure 16 shows the gradations before and after compaction by the modified proctor.   This is the laboratory test result and should be verified by field results in the future. The specific gravity of BCS was determined to be 2.38, indicating that this material is slightly lighter than natural aggregates, such as crushed limestone, sand, gravel, etc.
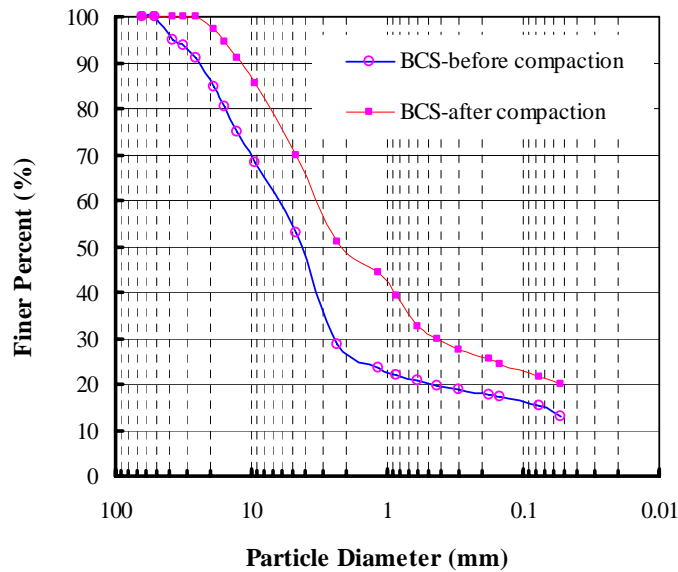
Figure 16
Particle size distribution of raw BCS before and after modified compaction

BCS requires a special drying condition of low temperature to prevent the phase transitions among different gypsum bearing materials as discussed previously. Figures 17 and 18 show the moisture variations of BCS with time in a 40°C oven and CoreDry, respectively. In a 40°C oven at least 24 hours was required for drying a BCS sample regardless of its gradation. In the CoreDry about 30 minutes were required for drying a 100-gram BCS sample with the minus-4 portion, and about 100 minutes were required for drying a 500-gram BCS sample with the entire gradation. Moisture content determined by the CoreDry was plotted against that obtained by a 40°C oven in figure 19, which indicates that the moisture content determined by the CoreDry device is good enough to represent the free moisture content of BCS. This device has the potential to be used in a field construction to control the compaction moisture of BCS.
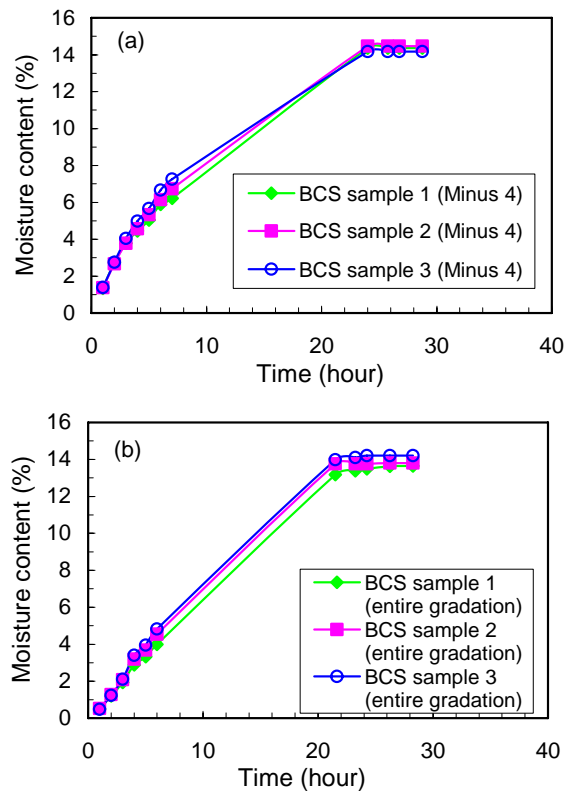
Figure 17
Moisture variation of BCS with time in a 40°C oven: (a) BCS with minus-4 portion;
and (b) BCS with the entire gradation
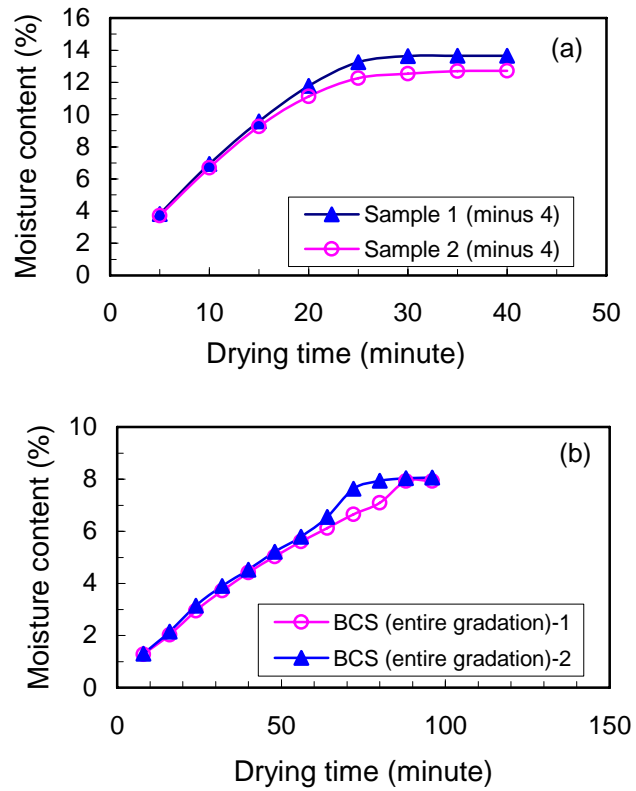
Figure 18
Calibration curve for drying: (a) BCS with minus-4 portion; and (b) BCS with the entire gradation
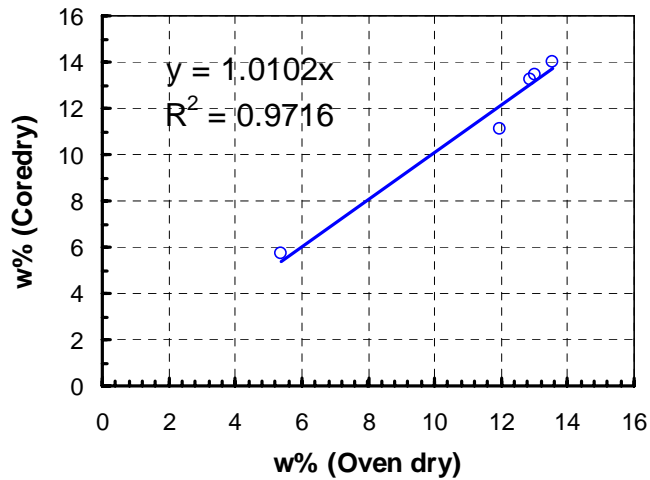
Figure 19
Comparison of moisture content determined from CoreDry and a 40°C oven

Figure 20 shows the compaction curves of the minus-4 BCS under standard and modified compaction with a 4-inch mold. The maximum dry unit weights are 100.5 *pcf* (15.78 kN/m^3) and 109.2 *pcf* (17.14 kN/m^3) with the optimum water content at 12 percent for both the standard and modified Proctor procedures. Figure 21 is the compaction curve of raw BCS with the entire gradation using a 6-inch mold.
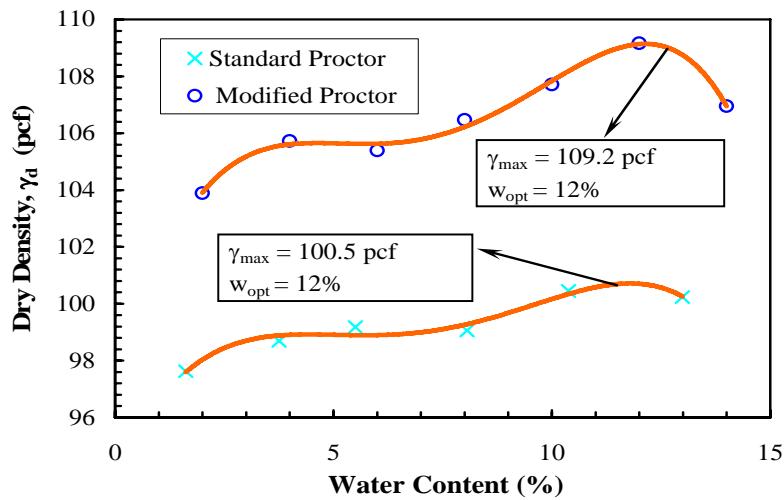
Figure 20
Compaction curves of minus-4 BCS
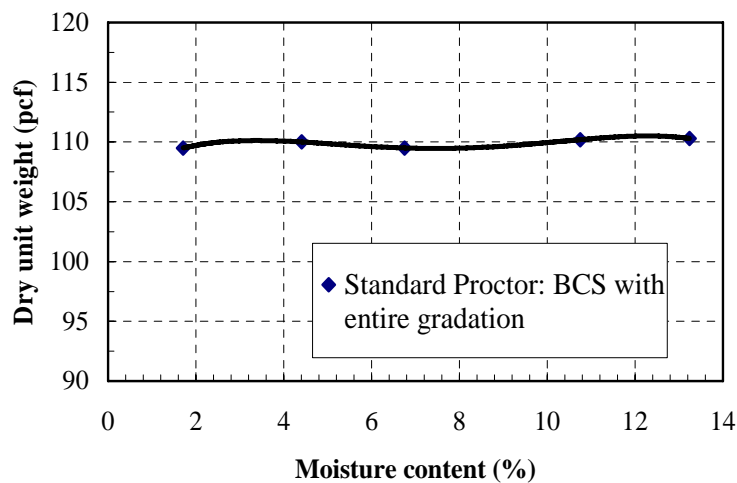
Figure 21
Compaction curves of regular raw BCS

Influence Factors on UCS of Non-stabilized BCS. The factors such as dry unit weight, curing condition, curing time, and moisture content at break have the potential to affect the UCS of non-stabilized BCS.

UCS versus Dry unit weight. Planned moisture contents and dry unit weights were 6, 8, 12 percent and 90, 93, 95 *pcf*, respectively. Table 7 summarizes the detail information of tested samples and their strengths. Very little free moisture content remained in these samples when they were loaded, as shown in table 7. Thus, it is reasonable to exclude moisture content's influence on UCS.

Table 7
Summary of samples molded by "compression" procedure

Sample ID	γ_d (pcf)[a]	w_i [b] (%)	w_f [c] (%)	UCS (psi)[d]
K-I-1	90.5	5.3	0.030	65.4
K-I-2	93.0	5.8	0.010	149.8
K-I-3	95.0	6.6	0.001	180.8
K-II-1	89.9	8.0	0.001	72.7
K-II-2	93.2	7.4	0.002	153.5
K-II-3	94.5	8.0	0.001	209.2
K-III-1	89.6	11.3	0.010	106.0
K-III-2	92.4	11.4	0.030	143.7
K-III-3	95.3	11.5	0.020	220.8

[a] γ_d is the dry unit weight of sample; [b] w_i is the initial moisture content; [c] w_f is the final moisture content; and [d] all of these samples were cured in air for 28 days.

Figure 22 shows the linear relationships between UCS and dry unit weight at each initial molding moisture content and indicates that UCS values increased with dry unit weight in general.
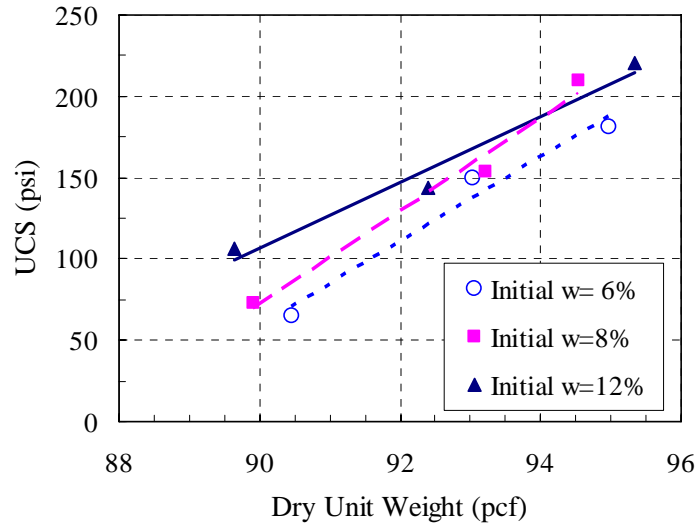
Figure 22
Variation of UCS with dry unit weight

UCS versus Curing Ages. Three samples were molded by the modified Proctor procedure at an initial moisture content of 14 percent, which was within the moisture range of field construction. These samples were then wrapped in plastic bags and cured in a 100 percent relative humidity room. UCS values of these samples at curing ages of 7, 14, and 28 days were 60.9, 60.3, and 54.5 psi, respectively, with final moisture contents of 6.9, 6.8, and 6.5 percent, respectively. The results indicate that the curing ages did not significantly affect the UCS of non-stabilized BCS. Neither pozzolanic nor hydrate reactions occurred much during the curing to enhance the strength of BCS.

UCS versus Moisture Content. Table 8 summarizes the specimens tested to investigate the influence of moisture on the UCS of BCS. As discussed previously, one set of samples, designated as set I, was under various curing conditions and tested at various time intervals at different final moisture contents, w_f (wet→ dry).   Since curing ages do not have an appreciable influence on BCS strength, the difference in strength among the samples in set I can be reasonably attributed to the final moisture content. The second set of samples was cured from dry to wet as discussed before in methodology (dry→wet).

Table 8
Variation of UCS with final moisture content

Sample ID	γ_d [a] (pcf)	w_f [b] (%)	UCS[c] (psi)	Curing
Wet→ dry				
BCS-1	102.3	0.08	368.5	50RH[d]
BCS-2	104.2	0.10	279.8	50RH
BCS-3	104.7	0.60	192.7	50RH
BCS-4	105.0	0.70	138.3	50RH
BCS-5	104.3	2.20	112.5	50RH
BCS-6	104.1	2.80	103.9	50RH
BCS-7	104.6	3.10	88.0	50RH
BCS-8	104.3	5.50	63.7	50RH
BCS-9	104.7	7.00	59.3	50RH
BCS-10	104.2	10.50	23.6	100RH
Dry→ wet				
BCS-I	105.5	11.10	26.0	50RH
BCS-II	104.7	10.20	25.6	50RH
BCS-III	104.8	10.00	30.1	50RH
BCS-IV	104.7	6.30	34.9	50RH
BCS-V	104.6	5.90	35.9	50RH
BCS-VI	104.1	2.70	124.5	50RH
BCS-VII	102.9	2.20	138.3	50RH

[a]γ_d is the dry unit weight when a sample is molded; [b]w_f is the final moisture content in percent; [c]UCS is unconfined compression strength; and [d]RH means relative humidity.

The comparison of the UCS results from these two sets of specimens illustrates that the final moisture content, w_f, at sample break controls the strength of non-stabilized BCS, as shown in figure 23. In this figure, open circles (wet→ dry) represent set I samples, and filled squares (dry→wet) represent set II samples. The UCS values of samples from set I and set II were close, provided their final moisture content were the same. The relationship between UCS and final moisture content is roughly reversible (i.e., UCS increases when a BCS sample desiccates; conversely, UCS decreases when a dry BCS sample is dampened).
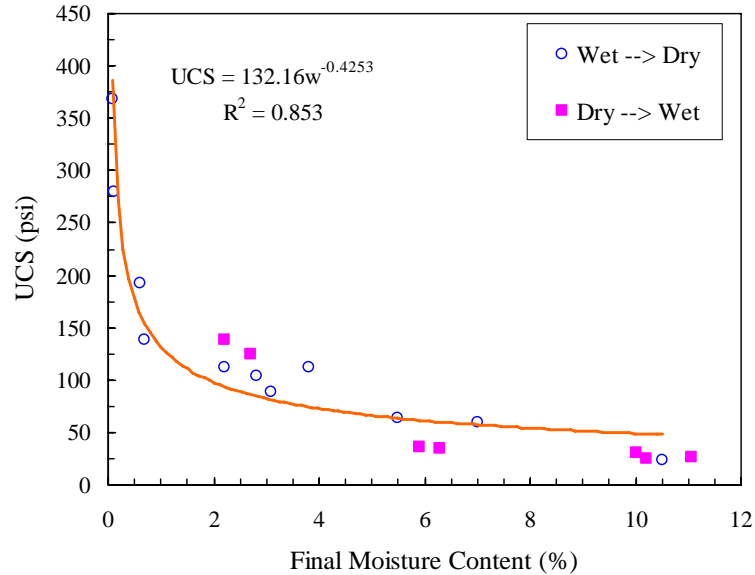
Figure 23
Deterioration of UCSs with final moisture content

Apparently, the UCS fell rapidly as final moisture content at sample break increased. Only about one-third of the UCS in a dry state was sustained once the moisture content increased as little as two percent, as shown in figure 23. Therefore, non-stabilized BCS can perform badly in a wet environment and a good drainage is important for this material *[22]*.

Curing Conditions. The final moisture content of BCS samples depends mainly on initial moisture content and curing conditions, especially relative humidity. Obviously, the moisture evaporation rate in lower relative humidity environments is higher than that in higher relative humidity environments. So, samples cured in lower relative humidity rooms usually have lower final moisture contents at the same curing age, resulting in higher strength. Thus, curing conditions affect the UCS of non-stabilized BCS samples through the final moisture content. This observation implies that a hot, dry season is favorable for field performance of a non-stabilized BCS base.

Strength Development of Non-stabilized BCS

The strength development of non-stabilized BCS can be interpreted from a microstructural perspective as follows. Test results indicate that both dry density and moisture content affect UCS of non-stabilized BCS, but the influence of moisture on strength is dominant. The interfacial free energy concept explains the water-dependent strength of BCS material and its water sensitivity *[7]*. This concept suggests that the strength of BCS mainly results from the strong electrostatic interactions between gypsum crystal particles. These interactions can be partially or totally shielded by the presence of free water, resulting in the weakening of the solid structures and the subsequent degradation of mechanical strength. Conversely, the bonds between gypsum crystal particles can re-form, allowing gypsum to regain its strength when such free water leaves the crystal interfaces, usually by evaporation. It follows that weakening or recovering the strength of gypsum is a reversible processes, largely dependent on the presence or absence of free water at the interfaces.

Stabilized BCS

GGBFS Stabilization – Laboratory Mixed. The test results of the GGBFS stabilized minus-4 BCS include the strength, durability, and volumetric change of the mixture.

Strength. Figure 24 shows that the strength of minus-4 BCS stabilized with 10 percent GGBFS by weight increased consistently with curing time, with the greatest growth occurring between 14 and 28 days. The UCS of samples tested without water soaking were 69.5, 202.5, and 966.5 psi at 7, 14, and 28 days curing, respectively; and were 61.2, 181.5, and 806.5 psi at 7, 14, and 28 days curing, respectively, after soaked in water for 4 hours. The UCS ratio defined previously for water resistance was 0.88, 0.90, and 0.83 after 7, 14, and 28 days of curing, respectively, compared to almost zero for non-stabilized BCS *[2]*. Therefore, in addition to the high long term strength, the water resistance of

GGBFS-stabilized BCS at various curing ages was significantly enhanced compared to the non-stabilized BCS.
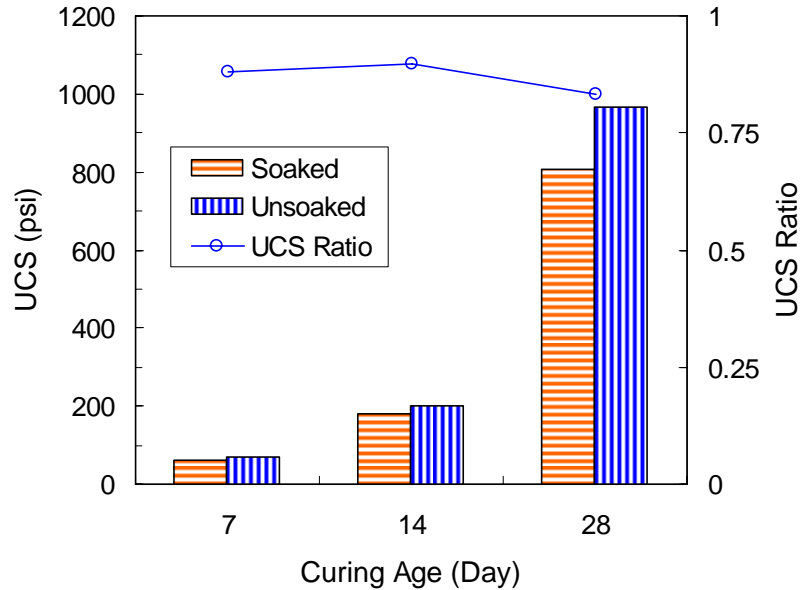
Figure 24
UCSs of minus-4 BCS stabilized with 10 percent GGBFS by weight at various curing ages

The elevated strength and enhanced water resistance of GGBFS-stabilized minus-4 BCS is primarily due to the rock-like product of pozzolanic reactions between the BCS and GGBFS, as shown in figure 25. The fragile texture of non-stabilized minus-4 BCS is also illustrated in figure 25 for comparison. The underlying mechanism for the enhanced water resistance and improved strength is attributed to the microfiller effect and the pozzlolanic reaction between the BCS and GGBFS *[9]*. However, the GGBFS-stabilized minus-4 BCS does not obtain high early strength due to the slow reactivity of the GGBFS, as demonstrated in figure 24.

Figure 25
Pictures of (a) GGBFS-stabilized minus-4 BCS and (b) non-stabilized minus-4 BCS

Durability. Figures 26 and 27 are the durability test results of GGBFS-stabilized minus-4 BCS. Figure 26 shows the mass loss for each cycle and the cumulative mass loss. Figure 27 shows the volume change versus cycles and un-brushed reference sample's moisture content. The variation of its moisture content over wetting and drying cycles was marginal, fluctuating around 7.5 percent and no appreciable volumetric change was observed over the wetting and drying cycles (for instance, less than 0.8 percent of volumetric change allowed for Portland cement concrete).
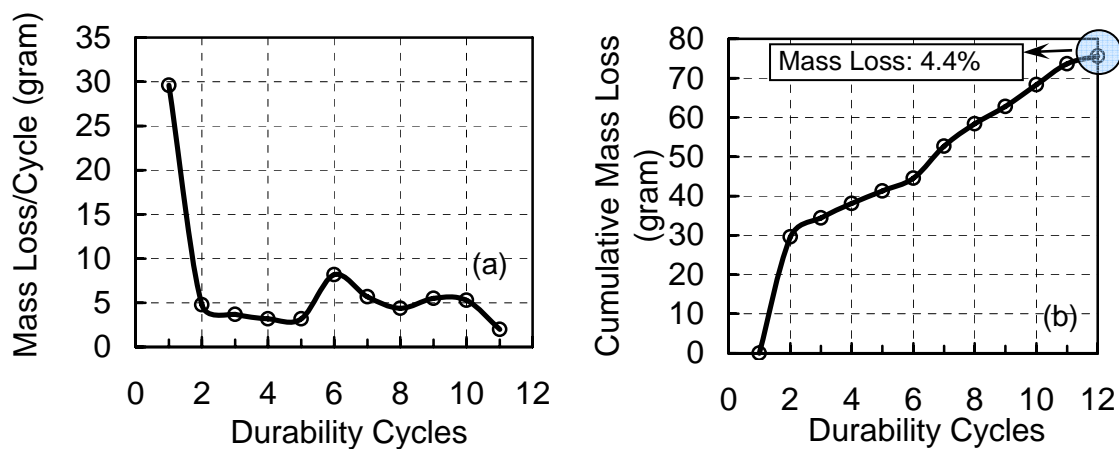
Figure 26
Mass loss of stabilized minus-4 BCS with 10 percent GGBFS by weight during durability test: (a) mass loss per cycle and (b) cumulative mass loss
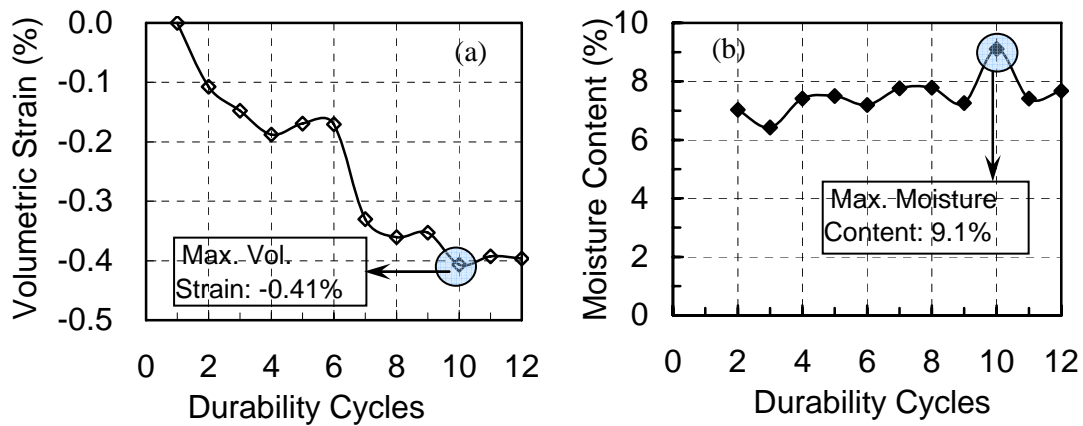
Figure 27
**(a) Volumetric variation of the reference sample during durability test and (b)
moisture variation of the reference sample during durability test**

After 12 wetting and drying cycles, the cumulative mass loss was small (about 4.4 percent), and the brushed sample still retained integration, as shown in figure 28.   In general, the durability test demonstrated that the minus-4 BCS stabilized with 10 percent GGBFS by weight had a good durability and long-term performance.
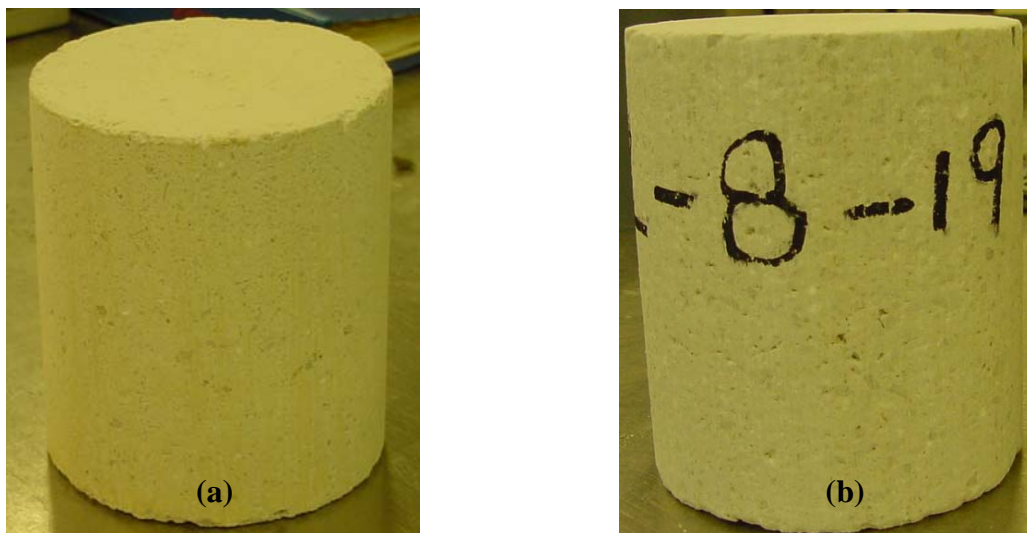
Figure 28
**GGBFS stabilized minus-4 BCS during durability test: (a) prior to the test; and (b) at
the end of the test**

Volumetric Change. Figure 29 shows the characteristics of volumetric change with time for the GGBFS-stabilized minus-4 BCS samples.   Most volumetric deformation occurred within the first 7 days, and the volumetric deformation that occurred after a 21-day curing was negligible. The maximum volumetric expansion of the stabilized material was less than 1 percent.
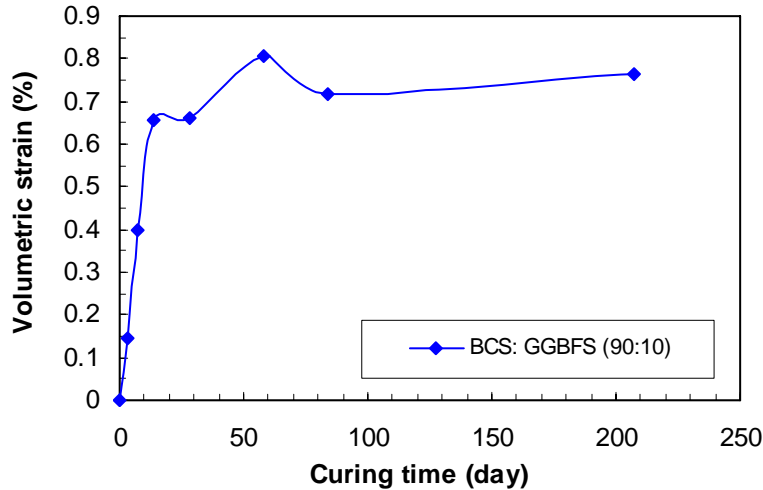
Figure 29
Volumetric expansion during curing for GGBFS stabilized minus-4 BCS

GGBFS Stabilization – Field Mixed. The addition of GGBFS in BCS changed the particle size distribution of raw BCS as shown in figure 30.   This figure shows the particle size distributions of the non-stabilized BCS and the BCS stabilized with GGBFS or fly ash after the stabilized BCS was mixed and set for a month without compaction. The raw BCS had a field moisture content of 20.1 percent prior to its stabilization. For the BCS-fly ash mixture, its field moisture content was 18.0 percent while it was 17.7 percent for the BCS-GGBFS mixture. These moisture content values were determined by the CoreDry machine in the laboratory. Note that the particle size distribution of the BCS-GGBFS mixture deviated considerably from those of the other two. The deviation was due to the particle conglomerations, which were the consequence of a reaction between the GGBFS and BCS.
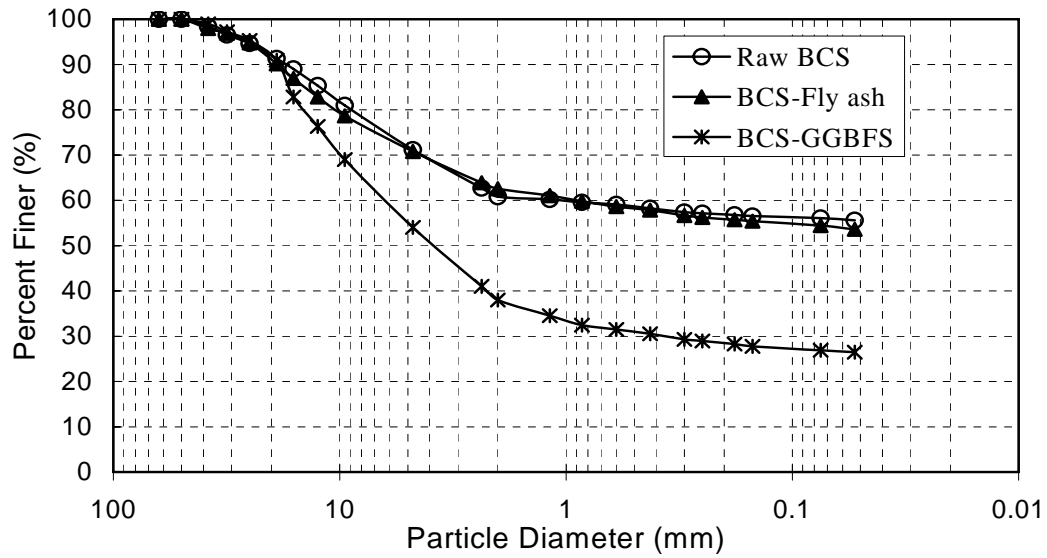
Figure 30
Particle size distribution of non-stabilized and stabilized BCS

UCS Results-Field Mixed. Table 9 shows the UCS results of the BCS samples stabilized with 10 percent GGBFS by volume, which were mixed in the field during the construction of field test sections, but molded within 3 hours in the laboratory.   The field mixing will be explained and discussed in the field construction section of this report.

Table 9
Summary of the field GGBFS-stabilized BCS samples molded at the laboratory

Sample	Time of Mold		Time of Break		UCS	Notes
	Moisture	Dry Unit Weight	Moisture	Dry Unit Weight		
	(%)	(pcf)	(%)	(pcf)	(psi)	
S-7A	17.9	98.7	13.7	102.5	93.1	Soaked*
S-7-B	17.1	99.4	15.7	100.6	106.6	Soaked
S-7-C	17.9	98.7	15.1	101.9	94.0	
S-7-D	18.1	98.1	15.4	100.0	122.7	
S-14-A	18.4	98.7	17.4	100.6	416.1	Soaked
S-14-B	22.0	94.9	15.4	100.6	463.4	Soaked
S-14-C	17.9	98.7	15.6	100.0	497.7	
S-14-D	16.9	100.0	14.4	101.9	577.2	
S-28-A	17.4	100.0	11.9	101.9	728.1	Soaked
S-28-B	16.1	100.0	12.1	100.6	722.6	Soaked
S-28-C	18.2	98.1	13.4	100.0	630.0	
S-28-D	17.4	99.4	13.2	100.6	715.3	
* means a four-hour submersion in water prior to UCS tests.						

Figure 31 plots the testing results. Much like the laboratory mixed minus-4 BCS stabilized with 10 percent GGBFS by weight, the field mixed BCS stabilized with 10 percent GGBFS by volume also exhibited a significant strength growth from 7 to 28 days, ranging from 108.3 psi (0.747 MPa) to 672.6 psi (4.638 MPa) without soaking and 99.9 psi (0.689 MPa) to 725.4 psi (5.001 MPa) after 4-hour soaking. The UCS ratio is also shown in figure 31. Apparently, a good water resistance was also achieved for the BCS stabilized with 10 percent GGBFS by volume and mixed in the field condition. Due to the difference in the gradation and GGBFS content used, the BCS stabilized with 10 percent GGBFS by volume had higher 7- and 14-day strengths, but lower 28-day strengths, as shown in figures 24 and 31.
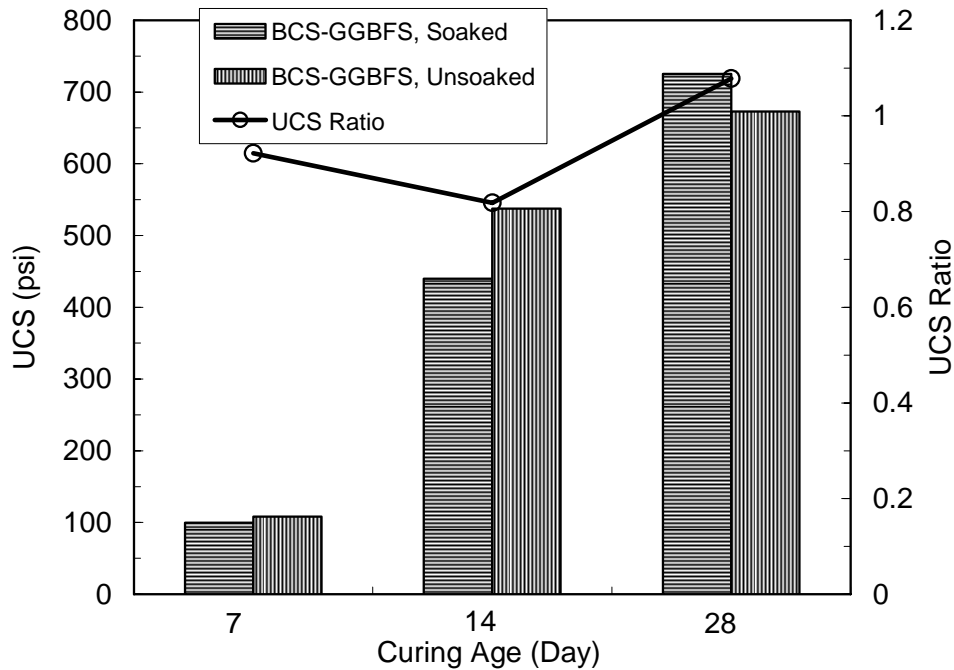
Figure 31
Unconfined compression strength of stabilized BCS at various curing ages: field mixed BCS-GGBFS

RLT Results for Resilient Modulus-Field Mixed. Figure 32 shows the resilient moduli of the GGBFS-stabilized BCS cured for 7- and 28-day periods. As expected, higher confined stresses resulted in higher resilient moduli for all the tested samples. Also, each sample's resilient modulus grew significantly with curing time and increased with the increase in deviator stress for samples cured for 28 days.   The resilient moduli at the anticipated working stress in pavements (e.g., 5 psi confining pressure and 9 psi deviator stress) were about 97.5 ksi (672.3 MPa) and 130.6 ksi (900.5 MPa) at 7 and 28 days of curing, respectively, compared to the crushed limestone used in Louisiana with a typical resilient modulus of 50 ksi.
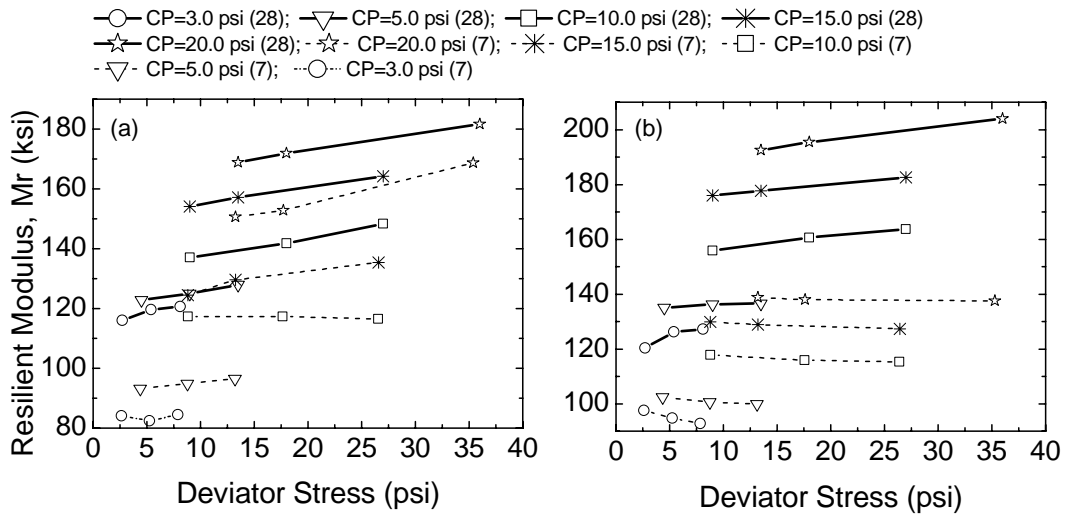
Figure 32
Resilient moduli for samples after 7 and 28 days of curing: (a) BCS stabilized with GGBFS, sample 1, and (b) BCS stabilized with GGBFS, sample 2

RLT Results for Permanent Deformation-Field Mixed. The permanent deformation of the GGBFS stabilized BCS was tested on the samples cured for 28 days. The tested samples were the same as ones for the resilient modulus, with their information listed in table 10. Figure 33 shows the test results by plotting permanent strain versus repeated load cycle. Generally, permanent deformation continued to grow as repeated loading proceeded but at gradually decreasing rates. It indicates again that adding GGBFS to raw BCS will greatly improve the engineering properties of the material and drastically reduce its permanent deformation which is related to pavement rutting in certain way.

Table 10
Summary of samples for resilient modulus and permanent deformation tests

Sample ID	w (%)	Dry Unit Weight (pcf)	D (in.)	H (in.)	H/D
BCS-Fly ash-1	17.5	110.2	5.97	11.61	1.95
BCS-Fly ash-2	17.5	100.6	6.05	11.59	1.92
BCS-GGBFS-1	13.5	105.1	6.03	11.60	1.92
BCS-GGBFS-2	13.5	101.9	6.04	11.90	1.97
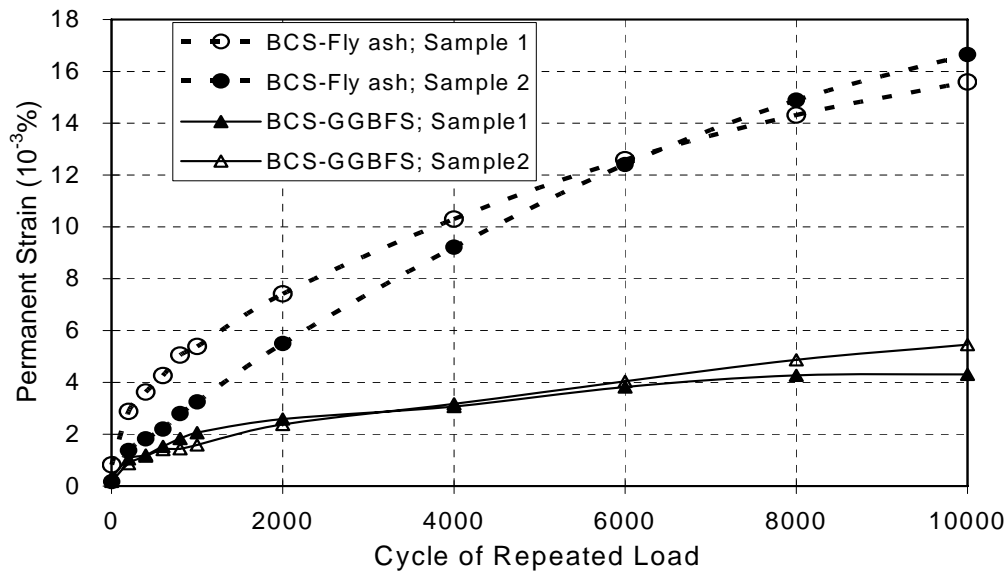
Figure 33
Permanent deformation of GGBFS stabilized BCS and fly ash treated BCS: samples mixed in the field and molded at the laboratory

Figure 33 also shows the permanent deformation of fly ash treated BCS samples, which will not be worse than the one of the raw BCS for comparison.   Apparently, the fly ash-treated samples underwent a much larger permanent deformation than the GGBFS-stabilized samples did, with their averaged permanent deformation about 4 times larger than those of the GGBFS-stabilized BCS.

GGBFS Stabilization – Field Cored.

UCS Results-Field Cored. Apart from the samples molded at the laboratory, four

good specimens of the GGBFS-stabilized section were cored from the ALF testing section after 35-day curing. Figure 34 shows the pictures of the cored samples. They were then trimmed like a regular concrete specimen. The resilient modulus test was conducted first, followed by the UCS test. Table 11 tabulates the information about the cored samples and their corresponding UCS test results.

Coring hole

Cored samples

Trimming

Trimmed sample
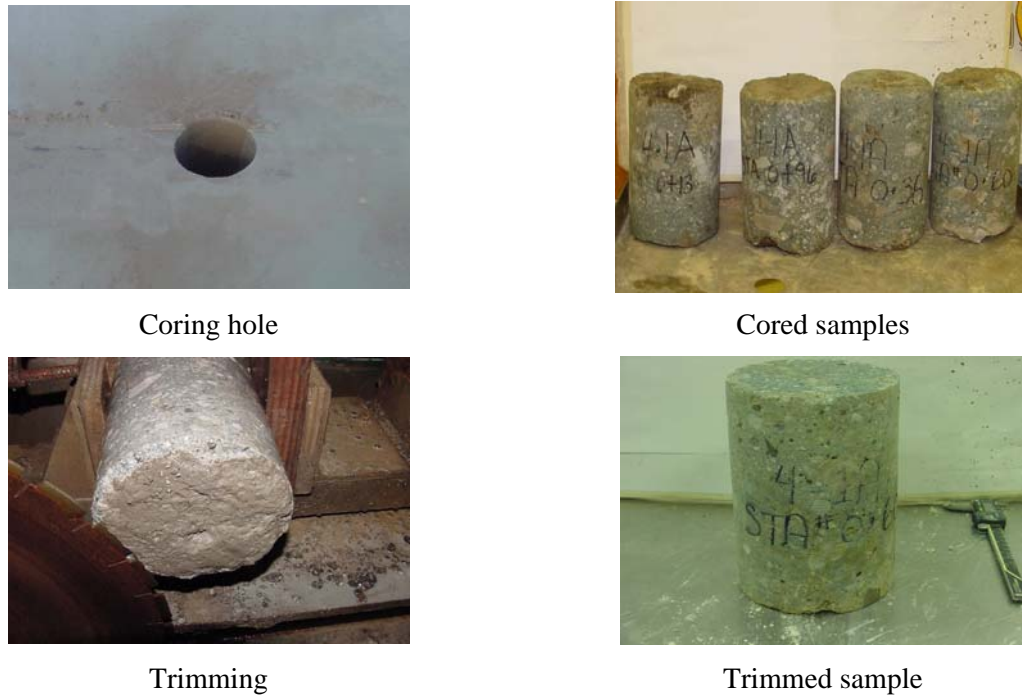
Figure 34
Samples cored from the test section

Table 11
Summary of the cored samples from the PRF test sections

Sample ID	Sta. No.	H /D	Dry Unit Weight (pcf)	UCS (psi)	w (%)
4-1A-1	0+30	1.36	100.8	823.1	14.0
4-1A-2	0+36	1.38	101.6	642.3	13.6
4-1A-3	0+60	1.38	101.9	827.7[a]	14.3
4-1A-4	0+96	1.37	100.8	802.6[b]	15.4

[a] UCS was determined after soaked for overnight; [b] UCS was determined after soaked for three days.

For the cored GGBFS-stabilized BCS samples, an average unsoaked UCS of 732.7 psi (5.05 MPa) and an average soaked UCS of 815.2 psi (5.62 MPa) were obtained, with a UCS ratio of 1.1. Compared with the UCS values in figures 31, which was based on the samples mixed in the field but molded in the laboratory, the GGBFS-stabilized BCS compacted in the field achieved a strength and water resistance comparable to those of the samples molded in the laboratory. This information confirmed the suitability of the in-situ mixing technique specified and the efficiency of the field curing condition specified.

RLT Results for Resilient Modulus-Field Cored. As mentioned before, RLT tests were also conducted on the cored GGBFS-stabilized samples. Figure 35 shows the resilient moduli for the cored samples, with two samples being soaked for at least 4 hours prior to the tests and the other two tested without soaking. The influence of confining pressure and deviator stress on resilient modulus was similar to that of the samples molded at the laboratory. The cored GGBFS-stabilized BCS still achieved fairly high resilient moduli, ranging from 51.1 ksi (352.1 MPa) to 74.4 ksi (513.0 MPa). As expected, the resilient moduli of the cored samples were less than those of the samples molded at the laboratory with more variation.
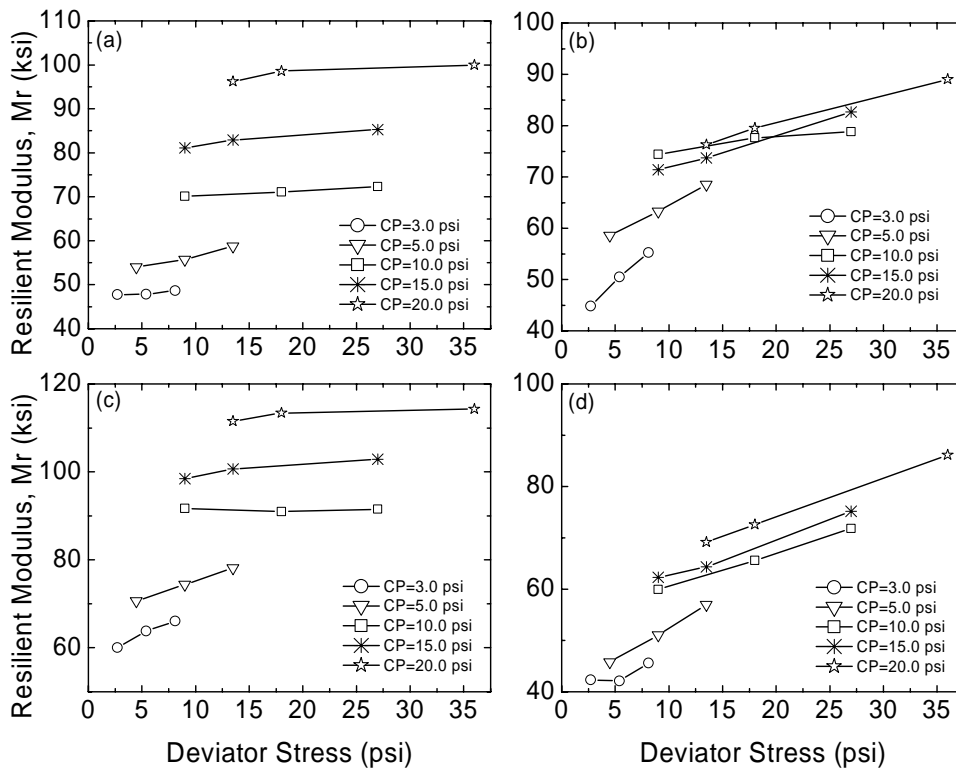
Figure 35
Resilient moduli for cored samples after 35 days of curing in the field: (a) BCS stabilized with GGBFS (unsoaked), from 4-1A (0+30); (b) BCS stabilized with GGBFS (unsoaked), from 4-1A (0+36); (c) BCS stabilized with GGBFS (soaked), from 4-1A (0+60); and (d) BCS stabilized with GGBFS (soaked), from 4-1A (0+96)

RLT Results for Permanent Deformation-Field Cored. The same testing procedure was used as that for the laboratory molded samples.   Figure 36 shows the permanent deformation results. It indicates that permanent strain varied considerably among the cored samples, ranging from 0.003 percent up to approximately 0.016 percent. Generally, the permanent strain of the cored samples was much larger than that of the samples molded in the laboratory, which to some extent can also be attributed to the coring and trimming disturbance.
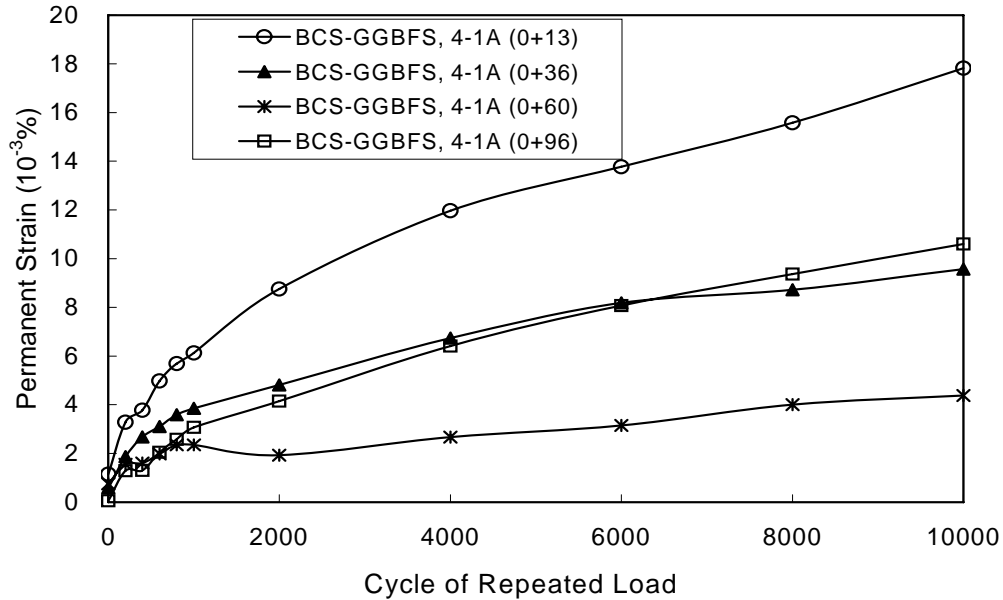
Figure 36
Permanent deformation of stabilized BCS (cored samples from the ALF test sections)

In general, the GGBFS-stabilized BCS is a strong base course material and thus will make a stronger structural pavement layer.

GGBFS Stabilization with Other Additives

     Strength. Table 12 shows the un-soaked UCS results of minus-4 BCS stabilized by GGBFS with other cementitious or non-cementitous materials.   Figure 37 compares the results of schemes in table 12 with one of the minus-4 BCS purely stabilized with GGBFS, and also shows the UCS ratio of soaked to un-soaked samples in parenthesis.   With regard to the average moisture contents at break for these specimens shown in table 13, all the mixture recipes (schemes) tested had a higher 7 day strength than the purely GGBFS stabilized minus-4 BCS had.   Cement was the most effective to increase the early strength of minus-4 BCS and a dose of 6 percent among these recipes is most cost effective to increase the strength of minus-4 BCS.

Table 12
Summary of minus-4 BCS stabilized with other additives

Mixtures	Proportion, %			Curing Time, day
BCS-GGBFS-Lime	96-3.3-0.7	94-5-1	91-7.5-1.5	
UCS, psi	295.9	397.4	398.8	7
BCS-GGBFS-Cement	96-3-1	94-4.5-1.5	91-6.75-2.25	
UCS, psi	590.3	706.3	723.7	7
BCS-GGBFS-lime-fly ash	96-2-0.67-1.33	94-3-1-2	91-4.5-1.5-3	
UCS, psi	232.1	255.3	259.6	7
BCS-GGBFS-Cement-fly ash	96-2-1.33-0.67	94-3-2-1	91-4.5-3-1.5	
UCS, psi	322	406.1	481.5	7
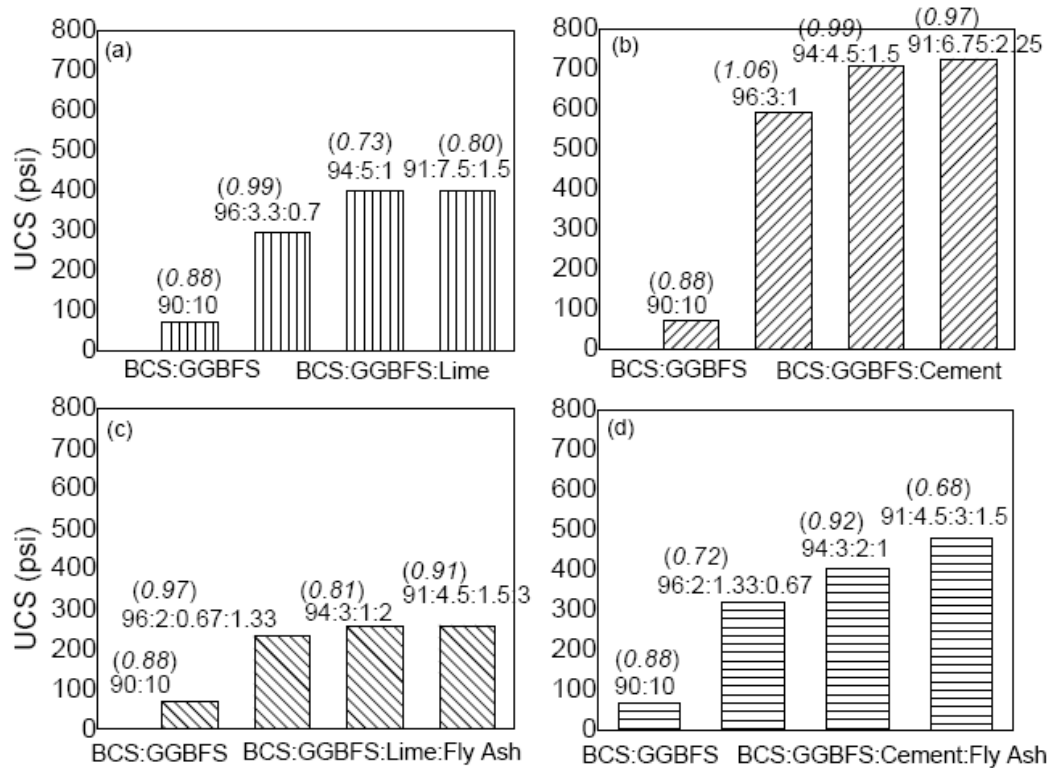
Figure 37
Seven-day unconfined compressive strengths of various stabilization schemes: (a) BCS-GGBFS-lime, (b) BCS-GGBFS-cement, (c) BCS-GGBFS-lime-fly ash, and (d) BCS-GGBFS-fly ash

Table 13
Sample moisture content at break

Mixtures	Average Moisture Content at Break, %		
	Unsoaked	Soaked	Curing Time, day
BCS-GGBFS	10.8	11.6	7
BCS-GGBFS-Lime	11.7	13.0	7
BCS-GGBFS-Cement	12.0	12.5	7
BCS-GGBFS-lime-fly ash	10.9	12.8	7
BCS-GGBFS-Cement-fly ash	11.3	12.4	7

Volumetric Change. Figures 38 shows the characteristics of volumetric change with time for these stabilized minus-4 BCS samples. For all the stabilization schemes, most volumetric deformation also occurred within the first seven days, and the volumetric deformation that occurred after a 21-day curing was negligible for most samples. Larger volumetric deformation was generally associated with higher stabilizer dosages. Of the stabilizers under investigation, the mixture of GGBFS, lime, and fly ash resulted in the largest volumetric expansion, followed by the GGBFS-cement-fly ash mixture, the GGBFS-lime mixture, the GGBFS-cement mixture, and GGBFS, in a descending order. The maximum volumetric expansions of 4.2, 2.9, and 1.95 percent for GGBFS-lime-fly ash mixture with the dosages of 9, 6, and 4 percent, respectively, occurred at 28, 56, and 14 days, respectively.
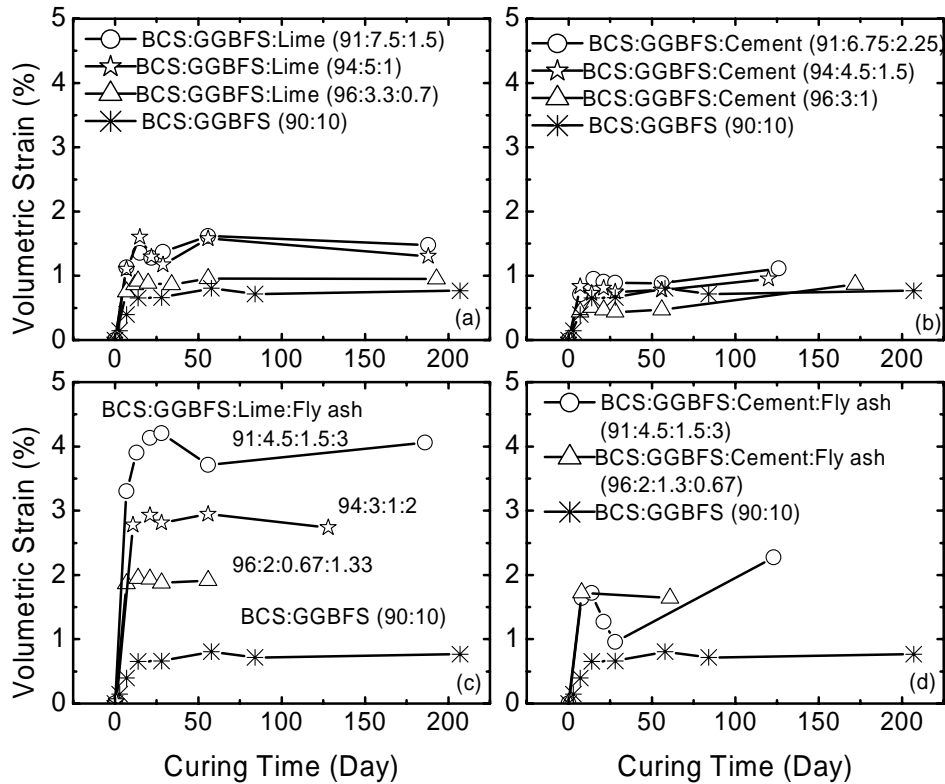
Figure 38
Volumetric expansion during curing for various stabilization schemes: (a) BCS-GGBFS-lime, (b) BCS-GGBFS-cement, (c) BCS-GGBFS-lime-fly ash, and (d) BCS-GGBFS-cement-fly ash

The GGBFS-cement-fly ash mixture had the second largest expansion, which was 2.3 percent for the sample with 9 percent stabilizer, and the expansion appeared to continuously increase after a 123-day curing. Unexpectedly, the GGBFS-lime mixture caused a larger volumetric expansion than the GGBFS-cement mixture. Nevertheless, the expansion in the samples stabilized by the GGBFS-lime mixture reached a steady value after 50 days, but the expansion in the samples stabilized by the GGBFS-cement mixture still increased slightly after a 175 days curing. Compared to samples stabilized only by GGBFS, the addition of a secondary stabilizer generally increased volumetric expansion. The formation of ettringite concurrent with the increase in UCS was attributed to the volumetric expansion.

The limited laboratory results of strength and volumetric change presented above indicate that it is possible to improve the early strength of GGBFS stabilized BCS without too much volumetric expansion by adding cement and lime, but fly ash is not recommended due to the potential expansion problem.   Field performance and material cost will dominate the selection of their combinations and more work is needed in this respect.

Fly-Ash Treatment – Field Mixed.

*Samples Molded at the Laboratory***.** Table 14 shows the results of the fly ash-treated BCS samples (15 percent by volume), which were mixed in the field during the construction of field test sections, but molded within 3 hours in the laboratory.

Table 14
Summary of the field fly ash-treated BCS samples molded at the laboratory

Sample	Time of Mold		Time of Break		UCS	Notes
	Moisture	Dry Unit Weight	Moisture	Dry Unit Weight	UCS	Notes
	(%)	(pcf)	(%)	(pcf)	(psi)	
F-7-A	18.0	98.7	18.6	98.1	32.9	soaked*
F-7-B	17.9	98.1	19.0	97.5	31.5	soaked
F-7-C	18.5	98.1	18.3	98.1	47.2	unsoaked
F-7-D	19.0	97.5	16.0	100.0	44.4	unsoaked
F-14-A	18.8	98.1	19.5	97.5	46.5	soaked
F-14-B	18.9	98.1	17.0	99.4	49.2	soaked
F-14-C	17.8	98.7	13.9	102.5	55.1	unsoaked
F-14-D	18.6	98.7	16.1	100.6	65.1	unsoaked
F-28-A	18.8	99.4	17.8	98.1	59.4	soaked
F-28-B	18.3	100.0	18.2	98.1	72.3	soaked
F-28-C	18.1	99.4	18.3	96.8	61.8	unsoaked
F-28-D	18.3	98.7	18.0	96.2	59.1	unsoaked
* four–hour submersion in water prior to UCS tests.						

The UCS of the fly ash treated-BCS increased slightly during the curing period from 7 to 28 days, as shown in figure 39. Its un-soaked UCS values ranged from 45.8 psi (0.316 MPa) to

60.5 psi (0.417 MPa), while the values ranged from 32.2 psi (0.222 MPa) to 65.9 psi (0.454 MPa) after soaking. The UCS ratio is also plotted in figure 39. Apparently, a good water resistance could also be achieved for the fly ash treated BCS with the UCS ratio larger than 0.7 if samples were molded in the laboratory.
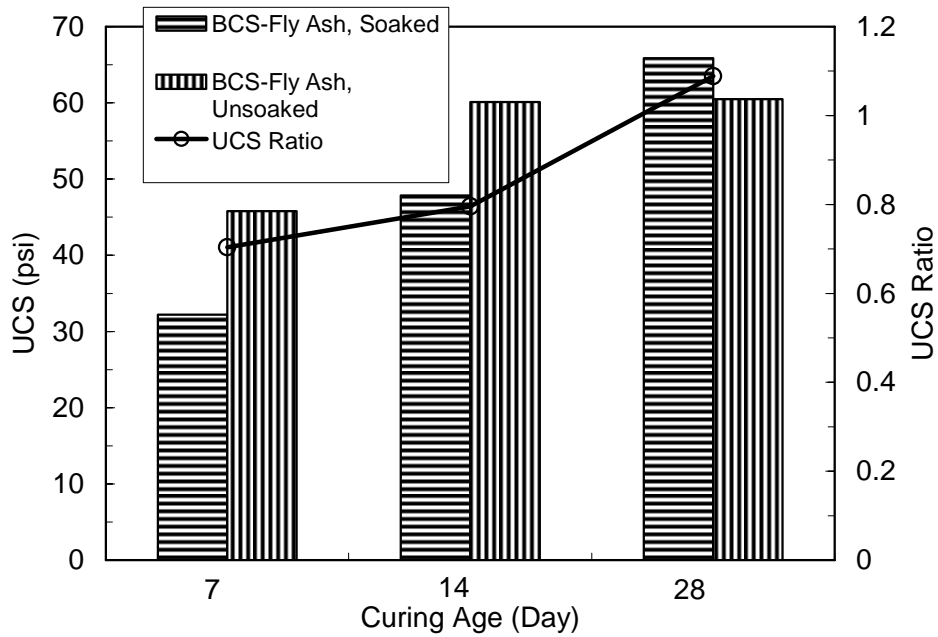
Figure 39
Unconfined compression strength of flay ash-stabilized BCS at various curing ages

The permanent deformation of fly ash treated BCS samples, which were mixed in the field and molded in the laboratory, was discussed previously with the results of GGBFS stabilized BCS.

Samples Cored at the ALF Test Sections. Only two samples of fly ash treated BCS were cored from the ALF testing section after 35-day curing due to the poor quality of the samples, as shown in figure 40. The information about the cored samples and their test results are tabulated in table 15.

Before soaking   After soaking

Figure 40
Cored fly ash stabilized BCS samples

Table 15
Summary of the cored samples from the ALF test sections

Sample ID	Sta. No.	H /D	Dry Unit Weight (pcf)	UCS (psi)	w (%)
4-2A-1	0+36	0.74	N/A[a]	19.6[b]	N/A
4-2A-2	0+60	1.00	N/A	N/A[c]	N/A

[a] data was not available; [b] UCS was determined in a dry condition; and [c] the sample fell apart before UCS test.

The cored fly ash treated BCS samples had an unsoaked UCS of 19.6 psi (135 kPa), and the soaked samples fell apart before the test as the photo shows. The strength results of the fly ash treated BCS, both molded in the laboratory and cored from the field, indicated the inefficiency of fly ash in stabilizing BCS.

In-Situ Test Results at the ALF Test Sections

Field Moisture

The raw BCS in the field had moisture content of 20.1 percent prior to its stabilization. The field moisture content of the BCS-fly ash mixture was 18.0 percent while it was 17.7 percent in the field for the BCS-GGBFS mixture.   A nuclear gauge measured a

29.9 percent and 26.9 percent of moisture contents for the BCS-fly ash and the BCS-GGBFS mixtures, respectively, which were much higher than those determined in the laboratory. Consequently, the dry unit weight measured by the nuclear gauge was greatly underestimated, as shown in table 16.   Therefore, a regular nuclear gauge has to be specifically calibrated for BCS before it can be used for the field construction control of the stabilized BCS.

Table 16
Field moisture content and dry unit weight of test sections

Lane No.	Test #	Field Dry Unit Weight, pcf	Moisture Content, %	Compaction, % Standard Proctor
	1	94.7	29.1	87.0
4-1A	2	92.4	30.9	85.0
	3	95.4	29.4	87.7
	1	96.2	27.6	81.0
4-2A	2	94.9	27.5	79.9
	3	95.8	26.7	80.7

Field Test Results

DCP. DCP tests were conducted before and after constructing the base courses (on Dec. 1, 2004). The DCP results, presented by penetration per blow in millimeters (often referred to as dynamic penetration index, DPI) versus elapsed time after the construction, are shown in figure 41 for various base courses. A higher penetration per blow generally indicates a lower strength for any tested material. For all the tested materials, the penetration per blow decreased significantly with the curing time, indicating an appreciable strength increase during this period. The strength increase most likely lay in hydration or pozzolanic reactions for the stabilized BCS, or in desiccation for the non-stabilized BCS. Compared with the fly ash-treated BCS, the GGBFS-stabilized BCS had a much lower average penetration per blow and thus a much higher strength, which is consistent with the results discussed previously. About a month after the construction, the GGBFS-stabilized BCS base was not penetrable.

BASE DCP VALUES
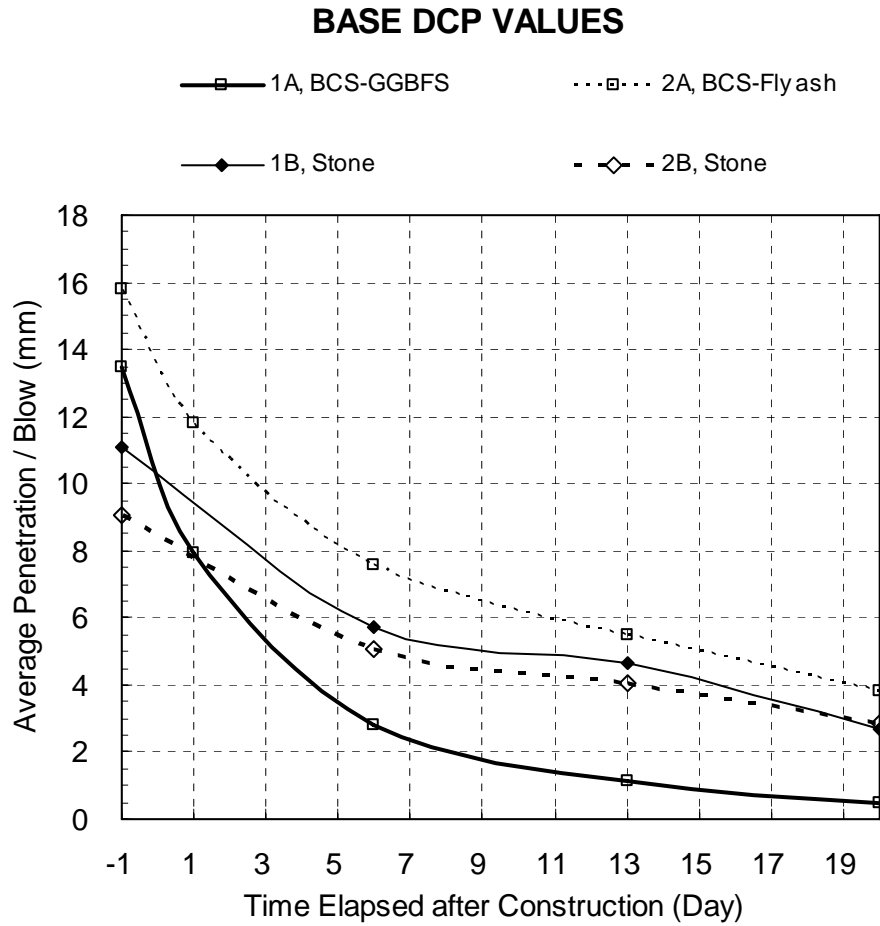
Figure 41
DCP results for various base course materials

FWD. FWD results obtained on the base layers of the testing sections at various curing ages are plotted in figure 42, with the deflections expressed in thousandths of inches. The figure indicates the relative stiffness of the tested materials at different time periods. By comparing the deflections in the 4-1A, 4-1B, and 4-2A sections, which all had a lime treated sub-base layer, the maximum deflection value was in the fly ash-treated BCS section, followed by the stone section and the GGBFS-stabilized BCS section. Thus, the relative magnitudes of stiffness among the materials were in a descending order as the GGBFS-stabilized BCS, the stone, and the fly ash-treated BCS. This trend also agreed with the resilient moduli obtained in the laboratory.
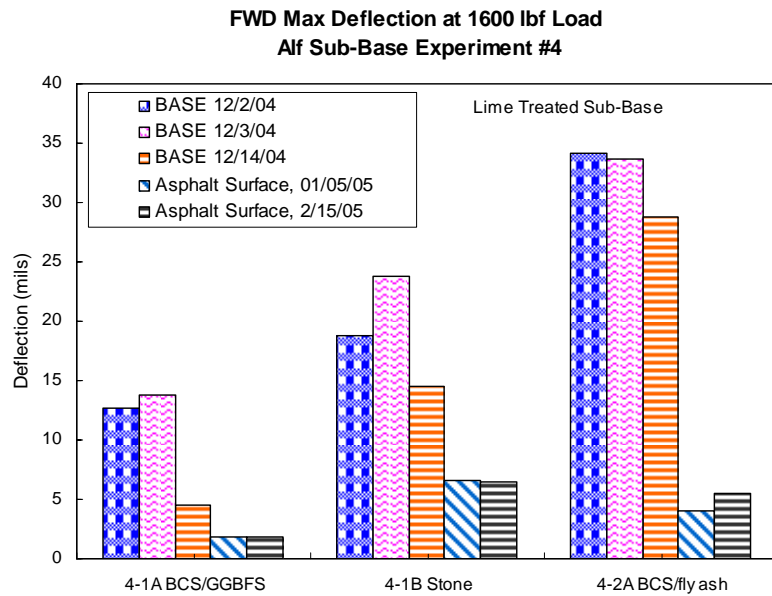
Figure 42
FWD deflections for various base course materials at different time periods

FWD tests were also conducted on the final surface layer of finished testing sections on 1/5/2005, 2/15/2005, and 4/4/2005, which corresponded to 35, 50, and 85 days curing, respectively. Figure 43 shows the back-calculated moduli at various curing ages. Among the base materials under investigation, the GGBFS-stabilized BCS achieved the highest resilient modulus at each curing age, about five times greater than that of other base materials. Only a slight increase or variation in resilient modulus was observed for other base materials during the 35- to 85-day curing period.
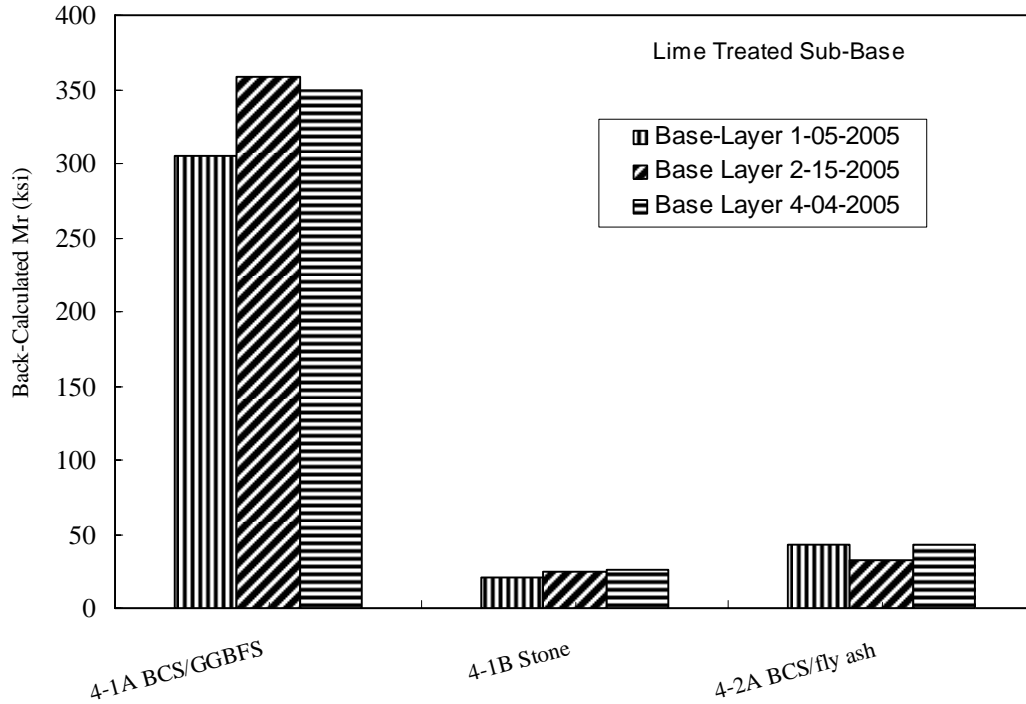
Figure 43
Back-calculated modulus from FWD data for base materials under investigation

DYNAFLECT. Figure 44 shows the values of structure number (SN) calculated from DYNAFLECT testing data conducted on 4/4/2005. It shows the same trend in the SN values as resilient modulus does among the base materials.
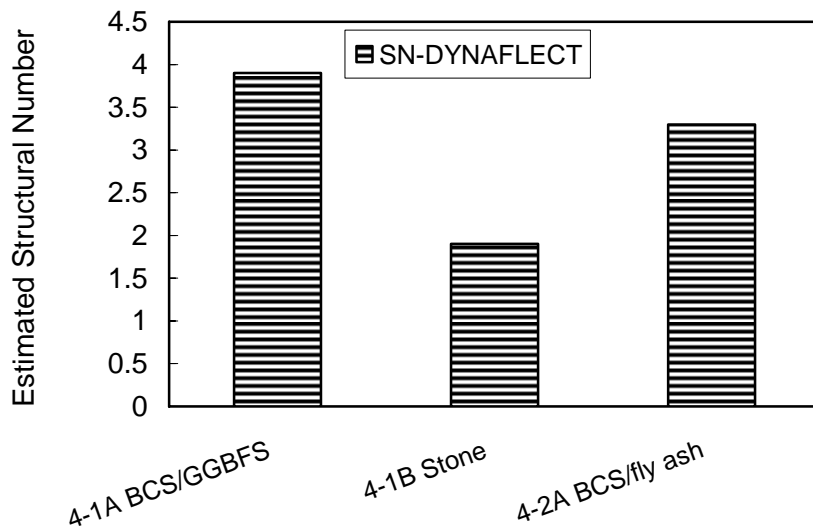
Figure 44
SN values from DYNAFLECT

Structural Layer Coefficient

   The current AASHTO pavement design guide uses a structural layer coefficient in flexible pavement design for a pavement surface, base, or sub–base layer, which can be correlated with CBR, R value, Texas triaxial classification, and resilient modulus of pavement materials. Table 17 summarizes the values of the structural layer coefficient, a, estimated from various data sources for the BCS stabilized by 10% GGBFS by volume. Equation 3 is used to estimate the structural layer coefficients based on the resilient moduli obtained through the laboratory and field tests for the material *[23]*.

$$a = 0.249 \log(M_r) - 0.977 \tag{3}$$

Where a is the structural layer coefficient for a base course material and M_r is the resilient modulus of the base course material in psi at the anticipated in-service stress level. For the DYNAFLECT data, the structural layer coefficient is calculated as

$$a = \frac{SN - a_1 \cdot d_1}{d} = \frac{SN - 0.44 \times 2}{8.5} \tag{4}$$

Where a_1 is the structural layer coefficient of top 2 inch asphalt layer; d_1 is its thickness; a is the structural layer coefficient of 8.5 inch stabilized BCS, d is its thickness. SN is the structure number determined by the DYNAFLECT on the test section.

Table 17
Summary of structural layer coefficient, *a*, estimated for BCS/GGBFS

Source of data	Layer coefficient, a	Curing time, day	Confined pressure, psi	Deviatoric stress, psi	Modulus, psi
Lab molded samples	0.287-0.293	28	3	5.4	119.6-126.5
Field cored samples	0.174-0.219	35	3	5.4	42.1-63.7
FWD tests	0.403	121			349.3
DYNAFLECT tests	0.356	121			

The layer coefficient from the field cored samples is the lowest due to the coring and trimming processes, and the field-testing values are at least 20 percent higher than the lab-test determined values.   It is conservatively estimated that the structural layer coefficient of GGBFS stabilized BCS (10 percent by volume) would be 0.3 for pavement design with some built-in safety for other unpredictable factors.

CONCLUSIONS AND SUMMARY

This research project has studied both regular raw and stabilized BCS for their physical and mechanical properties. The researchers discovered that moisture content controls the strength of raw BCS although other factors such as dry unit weight also influence the result. Curing conditions affect the strength of raw BCS through the change of moisture content in the material. The loss and regaining of strength is generally a reversible process and the presence of free water among gypsum crystal particles is the reason for this phenomenon.

BCS can be satisfactorily stabilized with 120 grade GGBFS. Both laboratory and field test results have indicated that BCS stabilized by 10 percent 120 grade GGBFS by volume can serve as a good pavement base. It is also possible to achieve good BCS stabilization results by using GGBFS mixtures with other cementitious materials, such as Portland cement or lime, as additives. The selection of such mixtures is controlled by cost, availability, construction requirement, etc. More specific conclusions are summarized as follows.

- o GGBFS-stabilized BCS performs more like lean cement concrete or strong soil cement than regular aggregates. Therefore, the only requirement on BCS's gradation will be its maximum aggregate size of 1.5 inch, which affects its workability, and the percent that passes the No. 4 sieve with an equivalent diameter less than 4.75mm, which controls the percent of GGBFS used.

- o The GGBFS-stabilized BCS achieves higher stiffness than that of the class II crushed limestone base material. Its structural layer coefficient can take a value of 0.3 for pavement design purpose.

- o The tentative construction specifications (Appendix A) used in the study proved to be adequate for the field construction. Therefore, it can be used with minor modification for future field test sections in highway projects.

- o Effectively monitoring field moisture content of BCS is still an issue that needs to be

addressed.   A nuclear gauge has to be specifically calibrated for BCS before it can be used for the construction quality control of BCS in the field.   The Coredry device used in this study can be one of the solutions.

o Both laboratory and field experience indicate that GGBFS stabilized BCS has to be cured at a moisture content of at least 5 percent higher than its optimum to perform well.

o The field test results from the LTRC PRF site indicate that the presence of coarse particles (retained at the No. 4 sieve) did not result in any undesirable effect on the stabilization.

o The GGBFS-stabilized BCS base still needs traffic loading control during its early curing time (first 7 days).

o Type C fly ash is not effective in stabilizing BCS as GGBFS does.

RECOMMENDATIONS

Researchers recommend that the LA DOTD consider building several field test sections in different traffic and environmental conditions using the GGBFS-stabilized BCS as pavement base course and that LTRC monitor the field performance of these test sections. A structural layer coefficient of 0.3 should be used for the GGBFS-stabilized BCS base to design these field testing sections. Both the raw BCS and Grade 120 GGBFS used should meet the current requirement of LA DOTD and ASCE specifications, respectively, and the raw BCS should be stabilized with 10 percent Grade 120 GGBFS by volume. Specifications in Appendix A can be modified accordingly to guard the field construction.

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Appendix A

Construction Specifications for Stabilized BCS

ITEM S-011, BCS Base Course, 8 ½" Depth: This item consist of placing and compacting a Blended Calcium Sulfate (BCS) material as shown in the plans, in accordance with these special provisions and section 302 of the Standard Specifications.

Section 302 of the 2000 Standard Specifications is amended as follows:

Section 302.   Description.   The third paragraph is amended to include the following:

(9) Blended Calcium Sulfate.

When public traffic is required to be placed on the completed, unsurfaced base course, the contractor shall maintain traffic in accordance with Subsections 105.15 and 105.16.

Subsection 302.02 Materials.   The first paragraph is amended to include the following:

Blended Calcium Sulfate   1003.01 & 1003.03 (g)

Subsection 302.04 General Construction Requirements.   This subsection is amended to include the following.

Blended calcium sulfate shall not be placed within ten feet (3.0m) of metal drainage structures.   The contractor will be allowed to substitute any untreated Class II base course material listed in Subsection 302.01.   Flowable fill under Section 710, or other approved backfill material in Section 701 shall be used to backfill the drainage structure.

Construction equipment required to place the blended calcium sulfate base course shall enter and exit as near as possible to the placement operation.   Any damage to the base course caused by the contractor's equipment shall be repaired by the contractor at his expense.

Subsection 302.05 Mixing.   Heading (f) is added as follows.

(f) Blended Calcium Sulfate: Calcium sulfate shall be blended with an approved aggregate or lime prior to placement.   The blended calcium sulfate material shall be uniformly mixed and sampled from dedicated stockpiles.

Subsection 302.06 Transporting and Placing on Subgrade.   This subsection is amended to include the following.

Water shall be added or other suitable means taken to prevent dust during the transporting and placing of dry blended calcium sulfate.

Subsection 302.07 Compacting and Finishing.   Heading (e) is added as follows.

(e) Blended Calcium Sulfate: Blended calcium sulfate shall be placed and spread on the subgrade and compacted to produce layers not exceeding 12 inched (300 mm) of compacted thickness.   During the application of water, apply an excess of 10 percent above optimum moisture.   After application of water, allow the moisture to reach equilibrium in the base before applying any rolling techniques.   Rolling of BCS is required to the edge of the embankment or subgrade.   Each layer shall be compacted to at least 95 percent of maximum dry density.   After compaction is accomplished, the base should be watered at least twice to satisfy moisture needs and curing.   Optimum moisture and maximum density

shall be determined in accordance with DOTD TR 418 Method G modified to include a maximum drying temperature of 140°F (60° C).

Subsection 302.09 Protection and Curing.   Heading (c) is added as follows.

(c) Blended Calcium Sulfate: Protection and curing of blended calcium sulfate shall be in accordance with Subsection 309.09(b).

Subsection 302.12 Acceptance Requirements.   Heading (a) is amended to include the following.

The acceptance requirements for blended calcium sulfate base course shall be the same as stone base course with the following modifications.   Upon completion of compaction operations, the density will be determined in accordance with DOTD TR 401 except that all moisture content de4terminations for density calculations shall be conducted by oven drying the material for 24 hours at 140°F (60°C).   A forced draft type oven capable of maintaining the temperature shall be provided by the contractor for field moisture content determination for density control.

BCS Base Course, 8 ½" Depth shall be measured per square yard and paid for at the contract unit price under:

Item S-011, BCS Base Course, 8 ½" Depth, per Square Yard.

BCS should be hauled to the site with no cost to contractor and slag (GGBFS) will be paid for at the contract unit price per square yard, which will include furnishing and placing slag at the specified rate of 10 percent by volume

ITEM S-012, BCS/Slag Stabilized Base Course, 8 ½" Depth: This item consist of placing and compacting a Blended Calcium Sulfate/ground granulated blast furnace slag (BCS/GGBFS) stabilized material as shown in the plans, in accordance with these special provisions and section 302 of the Standard Specifications.   This item shall be constructed in accordance with Item S-011 with the following modifications.

(e) BCS/GGBFS: Blended calcium sulfate shall be placed and spread on the subgrade and compacted to produce layers not exceeding 12 inch (300 mm) of compacted thickness. Place grade 120 GGBFS at the specified rate of 10 percent by volume.   Water needed to bring the moisture content of the mixture within 3 percent to 5 percent above optimum moisture shall be added and uniformly mixed (stabilizer) with the materials.   A minimum of two (2) passes with the mixer (stabilizer) will be required.   During the mixing process, water shall be added only through the spray bar of the in-place mixer that is adjusted to provide uniform coverage across the completed width of the roadway for the full depth of the base. The method of GGBFS distribution shall be such that the amount of GGBFS used can be readily determined.   Rolling of BCS is required to the edge of the embankment or subgrade.   Each layer shall be compacted to at least 95 percent of maximum dry density. After compaction is accomplished, the base should be watered at least twice to satisfy moisture needs and curing.   Optimum moisture and maximum density shall be determined in accordance with DOTD TR 418 Method G modified to include a maximum drying temperature of 104°F (40° C).

BCS/GGBFS Base Course, 8 ½" Depth shall be measured per square yard and paid for at the contract unit price under:

Item S-012, BCS/GGBFS Base Course, 8 ½" Depth, per Square Yard.